March 31, 2022

Afternoon Session

Plenary Discussions.

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>> Captioner is ready and standing by.

>> Can people hear us on Zoom? There are 15 people

connected.

>> We can hear you fine.

>> Thank you. We're just getting connected.

>> Can you see the slides from Zoom? You can't see the

slides yet?

>> No slides yet.

>> Can you see the webpage now?

>> Yes.

>> Perfect.

>> Is the microphone working?

>> I can hear fine. Seems to work.

They can see the slides?

>> Yes. It's connected.

>> I think can take off the mask, right?

>> All right. Very good. I'm glad to be here in person. I

was asked to provide a context for why we are pursuing a study on

the Higgs and for, as far as the future collider is concerned.

Very quickly, Higgs was discovered in 2012. And it's been

ten years. It's sometimes scary to realize that. So this is

Higgs at 2022. And we've come a long way since the discovery of

Higgs. We have all these wonderful results from our experimental

colleagues telling us all the different channel, different

couplings of a Higgs and so on and so forth.

And so since the discovery of the Higgs, the standard model

is self-consistent. Meaning that, you know, as quantum theory

standard model is quote unquote self-consistent all the way up to

the very high energy scale, but here I will use this opportunity

to remind everybody that self-consistent theory does not imply a

complete theory.

This is a fallacy that has been refuted many times

throughout the history of physics. For example, QED which is

just photons and electrons is self-consistent up to very high

energy but physics did not stop there.

A second example is Q CD, gluons and Quarks. Again, physics

didn't stop there.

Our standard model with one generation of fermion is

UV-complete. Again, but then who ordered the second and the

third generation of fermions.

This is not to mention the empirical evidence for the BSM

physics from dark matter, and dark energy and baryon asymmetry

and so on.

I wanted to hammer this message home that being

self-consistent does not imply the theory is complete. There are

still many questions and puzzles we don't understand.

Given this case, how do we find a path forward. Before the

discovery of Higgs we knew this big -- out there and we knew what

to look for and now everything is self-consistent. How do we

find the path forward.

I'm going to argue the rest of the way there are two paths

forward. We can test the prediction of the standard model. We

need to prioritize couplings that have yet to be established

experimentally. And also, for those that we have already been

measured, we need to over-constrain the coupling.

And the second direction, path forward is to ask the right

questions. We need to ask the right conceptual questions that

can't be answered by the standard model. And we need to also ask

the right empirical questions that cannot by answered by the

standard model.

So let me give you a quick overview, one slide overview of

the standard model Higgs boson. I want to emphasize something

that is not usually emphasized enough in the literature that is a

very specific particle with a foreign property. If you look at

the coupling of the Higgs to the massive gauge boson, it's the

mass of D divided by N.

The gluon and the photon and so on and so forth, once we

know the mass of the Higgs, we know the coupling to gluons and

photons.

For coupling to fermion, once we know the mass of fermion,

we know the coupling of the Higgs to the fermion.

And for self-coupling, if we know the mass of the Higgs, we

know the coupling of the self-coupling of the Higgs.

So this is a very nontrivial prediction that once all masses

are measured, there is no more free parameters. This is not a

case once you go beyond the standard model. This is a very

nontrivial prediction which is great in terms of testing the

standard model because that means there is no wiggle room. Once

we measure one deviation, we know it's not a standard model

Higgs.

And so we need to prioritize couplings that have yet to be

measured experimentally and there are some obvious targets to

look at. For example, Yukawaa couplings to first and second

generation fermions. The strange Quark or up down Quarks or

coupling to electrons and so on and so forth. We have made a lot

of progress in this regard but this is an obvious target to shoot

for.

There is the trilinear Higgs self-coupling that has received

a lot of attention already but we're not there yet in terms of

pining down the trilinear coupling. This is important for

measuring the potential of the Higgs.

There is also the 4-point HHVV coupling. This is a

prediction of gauge invariance. And we have not been able to

establish this important prediction of the standard model

experimentally.

So at the Higgs factory, both the trilinear and the quartic

couplings can be probed in the double Higgs and the VBF. These

are the contributions to the double Higgs production and the VBF.

You see a diagram with trilinear coupling and one contribution

coming from the VVHH coupling.

It becomes important, how do you disentangle these two

contributions in the future at the Higgs factory so we can affirm

and establish the presence of these two couplings.

Since we're on the topic of double Higgs, we can ask, why

stop at two Higgs?

Why not look for three Higgs, triple Higgs final state or

quadruple Higgs final state? These have not been searched for

experimentally but the final state can be produced in simple

extensions of two Higgs double model or a singlet with

significant rates.

This is a new frontier that is waiting Tor explored both at

the hadron and the lepton colliders. If you are doing the double

Higgs, why not triple Higgs or quadruple Higgs? For couplings

that have been established, we need to over constrain. This is

what our colleagues in flavor physics are very good at. We have

seen many times these constraints on the unitary triangle and the

constraints on the electroweak measurement.

Our colleagues from those -- are used to doing this

over-constraining the coupling. And that, this is something we

have to do for the Higgs. And of course, this is -- people have

been pursuing over constraining the coupling idea.

But if you look at the precision, you see, no, we are still

far away from being able to code a precision Higgs error, because

the -- is very large. Between 10 to 20 percent uncertainty.

And so one very important prediction of standard model Higgs

that needs to be measured precisely is certainly not with 20 to

10 percent uncertainty. That is unitarity constraint of the

standard model. Without the Higgs, the WW scattering amplitude

grows with energy in the standard model and this obviously

violates the integrity.

Once we include the Higgs, okay, and then the growth in the

WW scattering is canceled by the Higgs contribution and now

unitarity is preserved. This is provided that the HWW coupling

has precisely the form in the standard model.

Because you need something, you need these three diagram

contributions to cancel these two. So the coupling of the Higgs

to the WW and ZZ has to have very, very precise -- so this is an

extremely simple and economical solution. To add a scalar Higgs

to the -- violation in the welcomer W scattering.

This is only one problem, the problem is nature has never

chosen the simple solution before using a scalar particle to

unitarize the scattering of particles.

Pi Pi scattering has a similar issue of a -- violation. In

lower QCD, it's scattered by a series of resonances, not by one

particle. It's a series of heavy resonances including the spin

run rho me son.

In the standard model we're doing, only one single particle

to unitarize the WW scanner.

125 GeV Higgs only partially unitarize the VV scattering and

the HVV coupling will deviate from the standard model prediction.

Unitarization in the VV scattering is only tested to

10 percent uncertainty and this is clearly not sufficient for

such an important question.

At the end of the day I hope it's clear that precision is

key. And naturally, yes, what kind of precision is needed? What

are we talking? 10 percent, 1 percent, 21 percent?

In this record, I will give you a simple general argument

that it turns out by accident, in the standard model generic

deviations are quadratically 1 over mass of new physics.

That is, the generic deviation coming from the high scale

physics like -- V square over mass of new physics squared.

The fact this is a quadratic dependency is a nontrivial

accident coming from the standard model. In any case, if you put

in the mass of new physics at the 1 TeV, you see the expected

deviation is on the order of 5 percent.

So from this argument, you see that in order to establish

credible deviation we need Higgs factories with percent level

precision. That's the kind of precision we're talking about

here.

And so just to give you some idea very roughly, if we can

pin down the HWW coupling to 1 percent, we can probe generic

physics, new physics scale around 2 TeV. But if we can push for

the .1 percent, we can probe these scale new physics on the order

of 5 TeV.

And so that's about testing the prediction of standard

model. Now let me give you an example of asking the right

conceptual questions for which the standard model cannot answer.

And one very simple question is the following. What is the

Higgs made of?

This is something that, even a middle schooler could have

asked about the Higgs boson. What's it made of?

And everybody in this room has an advanced degree in physics

so we can ask the same question in a more sophisticated way.

What is the microscopic theory that gives rise to the Higgs boson

and the Mexican hat? We're all familiar with that in the

standard model, right?

I want to emphasize that we need to ask ourselves what is a

microscopic theory giving rise to these potentials?

And our colleagues in condensed matter physics are used to

asking and studying these kinds of questions. The most famous

example is the beautiful example of superconductivity discovered

in 1911.

Okay. Superconductivity was discovered in 1911 and in

1950s, Ginzburg-Landau theory offered a macroscopic theory for

conventional superconductivity.

And you see this looks precisely like the Mexican hat

potential that we have in the standard model for the Higgs.

So Ginzburg-Landau offered a macroscopic theory for

conductivity but it wasn't until our condensed matter colleague

asked what is a microscopic origin of the Ginzburg-Landau

potential? It wasn't until 1950 when Bardeen, Cooper and

Schrieffer provided the microscopic theory that allows for

interpreting the number of Cooper pairs and calculating the

Ginzburg-Landau potential.

And we do not have the corresponding microscopic theory for

the Higgs boson.

Okay. In fact, we have not even measured the

Ginzburg-Landau potential for the electroweak symmetry.

So the question can be reformulated in terms of quantum

criticality. Imagine a microscopic theory giving rise to the --

breaking and this is a quantum phase diagram. The coefficient

of -- is zero. On one side, the -- is zero. There is no

electric symmetry breaking.

On the other side, the -- is non-zero and there is electric

symmetry breaking. The question is we measure the Higgs as 1.5

GeV which is extremely close to the criticality.

The question is why? Why are we sitting so close to the

critical line.

One possibility is the critical line is selected dynamically

and this is the analogy of BCS theory. It goes by the name

Technicolor and it's strongly disfavored.

There are two popular explanations. One is composite Higgs

studies. A Nambu-Goldstone boson. And the other is critical

line is locus of enhanced symmetry. This is broken

supersymmetry. Everybody in the room knows the story.

We have not seen any signs of SUSY or composite Higgs.

What I want to emphasize, the facts that we haven't seen

signs of this only deepens the mystery of why we're sitting so

close to the critical line of EWSB.

It's humbling that after 40 years, our understanding is

still at the level of Ginzburg-Landau.

What we don't know, we do know is the electroweak symmetry

breaking is more exotic than the BCS theory of superconductivity.

This is why a prominent HEP theorist says the universe is not a

piece of crappy metal. Electro-symmetry is something more

exotic.

The question is what is it? We don't know. That is why we

need new machines to find out.

There are some excellent and empirical questions the

standard model cannot answer. There is dark matter, dark sector.

And CP violation and baryon asymmetry.

In the end these questions require us to have a program of

looking for deviation in the coupling structure of the Higgs

boson. Or rare and new decay channels of the Higgs boson. Or

partners of standard model top Quark that couple significantly to

the Higgs or just additional Higgs bosons.

Okay. Let me conclude.

I hope I convinced you that the Higgs boson is the most

exotic state of matter in nature. And the electroweak

criticality is the most bizarre type of quantum criticality we

have seen so far.

We don't know what kind of criticality is it. Understanding

is still preliminary at the level of Ginzburg-Landau and we need

to pin down a microscopic picture of the Higgs potential.

There is a rich program to be pursued at the percent-level

Higgs factory. Together with a high energy collider, we will be

exploring some of the deepest puzzles in physics.

Thank you.

>> Questions from outside or in the room?

I don't see any online.

>> Any questions in the room?

>> Let me just ask a simple question.

Higgs precision is of course, critical probe for all those

helping, understanding -- but you mentioned the high energy probe

as well. So if you have a choice, do you prefer precision or

high energy probes?

>> That's a loaded question. I think it's a trade off

between precision and high energy and I think this really depends

on what kinds of questions most interest you.

So, and they obviously offer different aspects of

information. But I would say as far as, if the question you care

most about is what is the Higgs made of? Then obviously high

energy is the way to go. Because then you're really asking when

you go down to very high energy, what is Higgs made of?

And -- but I can see the other type of question, when you

asked if you want to know, does the Higgs, is the Higgs -- the

dark sector or dark matter, maybe precision would buy you more in

that regard. It depends on the question you're mostly interested

in?

>> Any more questions?

Thank you.

>> We talk a lot about nonstandard model decays for the

Higgs which -- a that's the smoking gun, right. Life is easy.

As the LHC goes forward and we narrow down the branching

fractions, we limit the phase space for exotic decays while

keeping the linear mass dependence.

So then, at some point we have to ask the question, how much

phase space is left for the exotic decays? And do we envision

having a luminosity to produce that? I've never seen such a

plot. We talk about 97 percent of the Higgs decay space is maybe

narrowed down at some point. But it would be interesting to know

how at the end of HL-LHC, how much phase space is left and how

sensitive we have in a Higgs factory to explore that phase. If

there is more than one event, that is a problem, if we narrowed

it down too much?

>> That is obviously a very important question. It's the

interplay of HL-LHC and the Higgs factory. At the end of the

day, if we run the course for HL-LHC, it's not just phase space,

how much more room is there for nonstandard model Higgs? I think

that obviously has some people thinking about that question.

At this point of the game, it's really a detailed question

comparing the numbers. We just have to do the study and see what

the numbers, how the numbers stack up. It's very hard to be

standing here and talking off the top of my head. I recognize

that is an extremely important question that requires detailed

study.

>> For the Higgs factory, we know what -- initial state

beams we want, I think. For the very high energy collider,

what -- is 10 TeV enough or do we need to have the precision

Higgs factory measurements before we can decide what that is?

>> Very good. That's why I'm going to refer back to this

order of magnitude estimate between the precision and the scale

of new physics.

If we can nail down to .1 percent level precision in the

Higgs measurement, we'd roughly be probing 5 TeV scale of new

physics. If we still see no deviation at the level of 5 percent.

Then the next level should be much higher than 5 TeV because

we're already probing the 5 TeV indirectly using this .1 percent

of precision.

That is how I look at it.

>> This isn't a question. I wanted to comment on the

question that Bob raised.

If you look at the prospects for Higgs factories or HL-LHC,

it's hard to think you can bound the unobserved decays of the

Higgs boson to better than one percent branching ratios. But

more specific, you can get to 10 to the minus 3 or 4 levels and

for specific modes you can do extremely well with HL-LHC. We're

already at 10 to the minus 3 or decay of Higgs to 4 muons for

example.

So that's really the way to go. We just have to look for

the explicit modes, of course, you can do deeper searches at a

Hadron Collider and a more extensive search at an e. They

are quite complementary.

>> It's up to online. Can you unmute.

>> We have it.

>> We have it.

>> I'm here. Sorry.

>> No problem, when you have a moment if you can upload your

slides. Thank you.

>> Absolutely.

>> Okay. Fantastic. I have a pointer.

Fantastic. Okay. Great. First, I would like to thank the

organizers for having me here to talk about the Higgs precision

at the muon collider. Somehow this version is a little old and I

forgot to change the title.

Obviously, that's one big part of the talk. So that's why

it has some relic from the past.

Good. Obviously, it's a serious job so there will always be

technical difficulties. There is 1258 GeV S-channel resonant

Higgs program and the other is the high energy Higgs factory

program where we can produce the Higgs boson in a relatively

clean environment and are able to make high precision

measurements of the Higgs boson properties.

Let's just come to the very basics. I think this slide is a

bit old compared to what I uploaded. Basically, the proton

colliders, we are going to produce a lot of Higgs bosons. About

.15 billion Higgs at a HL-LHC. For typical lepton collider or

e, many producing -- Higgs from the associated production.

The Higgs strong process.

We're going to get around a million Higgs boson.

For the 125 GeV resonant factory, with 20 infers femptobarn

luminosity, we take into account the various factors of reduction

in the rate due to the various physical effects, we're going to

get about 70,000 to 280,000 Higgs bosons.

And on top of that, for 10 TeV muon collider where we mainly

produce the Higgs bosons through the WW fusion process which

should be in the updated slides on Indico. We're going to get

roughly 10 million Higgs bosons.

But let's go over the physics of the two programs one by

one.

So for instance, here is a typical -- you're going to get

for resonant Higgs factory. The Breit-Wigner peak is high, 70

pico barn. After the spread radiation and the scanning effect,

you get the effective cross section around the order of

10picobarn.

But with a lot of work trying to take this effect into

account and try to understand what is the Higgs precision program

at the Higgs factory.

The open questions include what's the scanning strategy and

what's the overall Higgs precision you can get? Those questions,

we made an attempt to address all these questions in recent our

study and I will show you the results of such an analysis.

So we see a strong correlation even though we can measure

the Higgs through a landscape scanning. However, it's clearly

correlated with the signal strength you are getting.

Because if the waist is bigger, without changing the

couplings the rate is lower. The lowering coupling can -- this

effect.

There's a large waist and large waist corresponding to

larger coupling and they have correlations. However, this

correlation direction is different from a normal flat direction

in other Higgs global fits. In that sense, it's already --

[inaudible] the muon collider resonant Higgs factory provides you

some information about Higgs waist in a very unique way.

So, of course, one needs to understand how the precision

scales with muon collider luminosity. We can extrapolate the

Higgs precisions through such understanding of this kind of

complex -- fit.

So just want everybody to know the Snowmass muon collider

for benchmark luminosity of a 125 GeV Higgs factory is around 20

inverse femptobarn which will provide you 2 percent of Higgs --

precision.

And further, we understand that Higgs width is a unique

parameter that enters our coupling extractions, just like every

exclusive measurement is proportional to the coupling strengths

and vertex and divided by the total width if we integrate over

the Higgs.

The width enters the coupling extraction in this way and

that is why the width is a very important quantity in our way to

understanding the Higgs precision properties.

So we perform, for the first time, a really comprehensive

study not only discussing in detail about how to performance such

a scan but also study the different exclusive channels just to

give us a sense of the signals and backgrounds and various

detector effects.

But the precision for those exclusive channels are labeled

in the last column. We generically get good sensitivities for

ttbar channel and for the tau lepton channel we get 2.4 percent

precision.

We can also study the diboson channels, the WW star and ZZ

star. At 125 GeV resonants Higgs factory, the background

actually is much lower compared to the signal to noise ratio is

higher compared to other machines because there is no -- to worry

about.

To fake such a signal of diboson, you have to be similarly

that process or some radioactive process.

So that's why we -- better Higgs to diboson precision in

those channels.

Let's take a look at the Higgs precision program result to

the 125 GeV resonant Higgs factory.

The horizontal axis is the various standard model couplings

where the width is a free parameter. The gray box is high lumi

directions. The gray bar here is really illustrative.

If you no longer set the width as a free parameter, you see

the horizontal black bars.

So what's interesting to pay attention to is the muon

collider in these blue bars, what's the precision they can

achieve. And comparatively to a typical Higgs factory.

So the impression we can have is the muon collider width

is -- new measurement. The correlations are different. The

second thing we can extract is of course, the muon collider

cannot determine the Higgs to ZZ coupling as precise as other

Higgs factories but on the other hand you can determine the muon

to unprecedented precision of .3 percent.

What is interesting is to see the complementarity. I'm

collecting maybe 30 percent of the Higgs, number of Higgs

comparing to the typical Higgs factory. Those 30 percent of

Higgs is not just a statistical addition. Combination between

the Higgs and the future, 125 GeV muon collider and the future

lepton collider give you better results that leads to improvement

that is more obvious than you naively expect from statistics.

This is really because the correlations are quite different.

And in that sense, it's a very nice program.

So here for the first time we achieve the global picture of

the 125 GeV muon collider, Higgs potential which will help us

with the planning.

And later today we'll hear more discussions about the muon

collider staging possibilities and, et cetera.

But here is the physical understanding.

So having said enough about the 125 GeV muon collider

program, we can move towards the higher energy. Which several

speakers and participants mentioned as high energy physicists we

all want to go to the high energy program, you know, sooner or

later or eventually.

We like the high energy profile. The high energy muon

collider program provides a vibrant and growing Higgs physics

program. Including the baseline precision coupling, the Higgs

self-coupling, and top Yukawa through interference and muon

Yukawa at different energies.

So here is a basic picture. I grabbed this from the recent

study from Matthew and Patrick.

On this axis is the exclusive, the precision of various

exclusive channels. As I mentioned earlier, the major production

for the single Higgs at the hadron muon collider is WW and cross

sections around one picobarn.

This allows us to collect 10 million Higgs.

There are many discussions about the precision and rated.

But what is interesting is say, take a look at what the Higgs

precision can achieve at high energy muon collider.

We can see that we can achieve many impressive numbers that

are really -- level. Like the gauge boson couplings, coupling to

gluons and photons, et cetera.

So here is just another representation that I made in recent

Snowmass contribution from the INCC.

So the different bars show the EFT fit with precision on

the -- and coefficients. May be more useful to look at the

right-hand which is a physics scale of those operators if we

assume the unity of the -- and coefficients.

We can see, the lower the better. That's a higher scale

we're probing. Through the multi-boson process we can probe

physics at much higher scale with a high energy collider with a

clean environment.

Regarding the Higgs physics, we can get from Higgs to --

coupling, tens of TeV of new physics which is great improvement

in our understanding that echoes what Ian just talked about. The

precision program does lead us to deep understanding of new

physics at higher scales.

So that's the baseline precision program. I also want to

mention the multi-Higgs opportunities here. Really, those

diagrams and double Higgs processes really allows us to extract

the Higgs multi-couplings to really percent level or sub percent

level from different processes.

So this enables the -- percent level Higgs couplings,

et cetera.

Here is another example of quart tick Higgs. It's a program

that many groups have tried to study the triple Higgs production

and tried to extract the coupling precisions.

You can see, they will ask to extract the coupling of the

quartic Higgs at the -- level which is a big improvement compared

to what we can do now.

Also, the top Yukawa coupling plays special roles in various

puzzles around the Higgs. It can be extracted in an interesting

way.

We know the Higgs uni -- is a WW ttbar process. That does

change the behavior of the ttbar productions with the -- high

energy muon colliders. From this study in the muon smasher in

this part, we can see that a few percent level precision of --

top Yukawa is possible.

I want to mention an interesting study trying to study the

Higgs radiation from the muons in the multi-boson process at high

energy muon collider. So because I'm -- the Higgs out of the

energetic muon, I can effectively probe the running or the Higgs

coupling at different scales. They're saying from those

multi-boson including Higgs process, one can extract the Higgs

muon Yukawa at tens of percent level.

It's not as precise as 125 GeV muon collider but it gives us

a very interesting, different probe of Yukawa.

So just I think I'm just in time. I just want to summarize

here. 125 GeV S-channel resonant Higgs factory provides a

distinctive measurement of Higgs width. It's complementary to

other lepton collider Higgs programs. And uniquely allows us to

have a subset of muon Yukawa determination. There is a lot of

hypothesis around muons and experimental hints. It's an

important input for us to decipher the myth around muons.

The global picture of 125 GeV Higgs is potential.

In the high energy muon collider part, there are many

possibilities. Higher energy allows us to do many kinds of

probes.

That covers the basic precision program, self-coupling, top

and Yukawa, et cetera. There are more discussions later today.

With that, I just conclude here. Thanks.

>> Thank you very much, any questions from in the room?

>> For the Higgs resonance program, what do you assume about

the machine energy width?

>> We assume the machine energy spread of .003 percent which

is 3 to the minus 5. That is one of the benchmarks pro-vet

moated in last Snowmass.

The physicists think that is reasonably optimistic scenario

that one can achieve?

>> This is comparable to what is being proposed for FCC-ee?

>> So to, okay, so that, I have to recall my memory. If my

memory is correct.

>> They want to get down to 10 to the minus 5 level.

>> I think this has to be similar to that.

>> For them it's incredibly difficult. You have to do a

correlation of position with energy in order to reach that.

This is also incorporated in the muon proposal?

>> I'm not an expert but after talking to our muon collider

experts, they think this is a reasonable benchmark. 8, 10 years

ago, last Snowmass people already think it was a possible

benchmark one can aim at.

>> Can I just ask a very naive question. You have the

transverse degrees of freedom. This requires a phase space

reduction from the original muon production in excess of 10 to

the 7?

>> I think that was it. But we can see, I believe in Mark's

talk we will really see the muon -- phase diagram and how we can

achieve that. One interesting point I learned from those

discussions is to achieve high energy muon collider, you need to

first try to cool, do a 60 (ph.) cooling and bit of recovery and

get to higher energy.

In that point of view, the phase space cooling requirement

for a muon collider Higgs factory is almost on the pathway

towards the high energy one. But there's other technological

challenges. I believe Mark will mention how to interface the

machine, et cetera. But it's really in the top -- [inaudible]

>> Okay. I look forward to it.

>> Hi Zhen. I have a question about the Higgs radiation and

the running. First of all, let my try to understand this, this

is really Higgs parton inside of the muon.

>> They discussed several scenarios. Having a discussion of

the running, you have to put into the model the context. They

can put in those, actually the models that give you -- factors,

et cetera. What they're trying to do is combine a series of

multi-boson production channels including single Higgs, double

Higgs as well as in some theories you can relate the muon Yukawa

shift to be a longitudinal boson production. They combine

various different channels in different frameworks you can

extract those.

>> So then quickly, for example, on this slide, this extra

dimension, the running is different. What's the size of this

extra dimension that is assumed?

>> I don't recall the detail. You can clearly see this

extra dimension enters at the scale, like, 5 to 10 --

>> That's what I thought. But okay. Fine. We can discuss

offline. By the time we get to that energy, we should be able to

see these -- directly.

>> That's exactly true and I think the authors promote this

as one example to see the running effect of the Yukawa couplings.

It doesn't mean this is exclusive to the best probe you can have

on those under lying theories. That is why they propose several

alternative frameworks to see.

>> Thank you.

>> Any more questions?

>> We have two questions on Zoom. Christof.

>> I have a question on the width of the Higgs? What is the

sensitivity you get?

>> Very nice. At 125 GeV muon collider, we wouldn't be able

to do directly an invisible Higgs search. In there, at the --

the confluence is coming from the total width measurement. For a

high energy muon collider, I don't think we will get the width

from the -- process but from the ZZ fusion process you will get

some sensitivity.

I don't have the number right now in my mind. But

Patrick -- it's still under study.

We don't know that number. Okay. But if I have to naively

guess, you know, it's statistically at best at percent level.

This is mini Higgs, .1 percent but there is background in those

processes.

>> That's what I'm confused about. FCC-hh is 10 to the

minus 4. I don't understand why you're so different.

>> That's a lengthy discussion. I think several members

here already discussed that privately. I think the FCC-hh study,

they were relying on some, how do I say, statistical

extrapolations of other uncertainties. And they also, if I

remember correctly, they somehow get a lot of sensitivities from

the GBH process which they claim the background can be controlled

to be low.

In my personal opinion, that is in question. But I think

more study are needed to understand that.

>> Thank you very much. I saw there was one more question

on Zoom.

>> I had essentially the same question.

>> Okay.

>> Thanks.

>> Great.

>> Since I have a microphone, we're talking about invisible,

we can do the exotic decay program very well. For both 125 GeV

and higher energy case. Just wanted to put some numbers into

perspective. On the talk -- sadly showed what's the exotic decay

projections at HL-LHC that is made by my team.

That is basically a few percent combining the direct and

indirect constraints. For the lepton colliders, by and large,

most of the channels are covered at 10 to the minus 4 level. If

one can make use of more of the full statistics you can reach 10

to the minus 6 level. There is room for us to explore new

physics in the exotic decay and you know -- physics have

couplings and we want to target lower branches.

In Tuesday's talk there was a particular target from the

single let enhanced electric phase transition. And they do want

to probe that region as well. I think this is another important

component of the Higgs program I didn't put in the slides.

>> Thank, okay.

Let's thank the speaker again, [Applause].

And then Saptaparna, can you share your slides?

>> One moment. I hope you can see that. Let me try to go

full screen. I hope this is good, right?

>> Yes. I think that looks good.

>> My slides should be updated if you are projecting what's

on Indico should be fine.

All right. Great. So first of all, thanks to the

organizers for inviting me to give this talk on behalf of CMS and

ATLAS specifically focusing on the HL-LHC projections and results

that were recently done as part of the Snowmass process.

So yes, this is sort of a Higgs aficionados exploration of

the HL-LHC.

So of course, as you all know, the Higgs boson is

inextricably connected to the LHC. The LHC was designed to

discover the Higgs. If you look at the technology report, the

goal was to understand -- we found the Higgs boson at an early

stage of the LHC physics program. So the ten years of this

program are close to ten years of the Higgs boson. The Higgs

will turn ten years in July of this year. Happy tenth berth day

to the Higgs and like I said, this ties in well with the ten

years of the LHC and this implies that in the ten years of the

LHC, 8 million Higgs bosons were found.

And if you look at this, there is a nice magazine article

that highlights some of the milestones of ten years of the LHC.

And there are some serious ones like the number of Higgs bosons

but other metrics like the number of cups of coffee consumed to

get us to this point.

10 million Higgs bosons took 8 million cups of coffee.

Where do we stand right now with respect to Run2? The mass

of the Higgs boson is known to precision of 11 percent. The

width is narrow resonance, it's 3.2 MeV. This is a really new

result that includes off-shell and on-shell modes. The off-shell

is important because of the way the Higgs interacts with the

massive bosons.

And the -- is measured for standard model particles and this

is a really a straight line. The slope is proportional to the

masses of these particles and all of this indicates that the

Higgs that we've seen is really a standard model Higgs boson.

And so I just have an illustration of the official plot

which looks like this. I know you've seen this in this workshop

before. I just wanted to give a sense of -- I don't want to

spend too much time on this plot, just so say this aligns nicely

with the standard model expectation.

So yes, I think we can say with some amount of confidence

this is really the standard model Higgs.

Of course, we can also use the Higgs as a probe for new

physics. And this leads to very interesting articles. I just

found this article recent article that says that the large Hadron

Collider ATLAS and CMS collaborations chase the invisible with

the Higgs boson. That means that the study was done to look for

nonstandard decay modes of the Higgs and the conclusion was there

is only a certain fraction or 15 to 18 percent of the time the

Higgs scan have a nonstandard decay model. But that was an upper

bound set.

I like these kinds of news articles and this is a rather

serious one and written well, but I do like these headlines that

really are eye catching.

So yes, the new Higgs boson can be used to look for new

physics.

Let's look at the LHC upgrade schedule. We are in 2022.

And this means that we are really at the precipice of Run2. And

the HL-LHC is going to be installed between 2026 to 2028 and the

plan is to be able to collect 300 to 4 houseworks reverse

femptobarn of data.

This is a huge dataset and we only analyzed a small fraction

of the dataset so far.

And I should also mention that collecting this amount of

data has its own challenges. There will be upgrades to the data

acquisition system that will be required to be given the large

amount of information that we will be collecting. Given our

detectors, we will have granular detectors collecting a lot of

data. And to be able to deal with this, we will need

considerable R&D for software and computing needs and there will

be upgrades that need to be designed for reconstruction.

A lot of data comes with its own set of caveats but it will

be an interesting and challenging time using all of the data

effectively.

Let me quickly point to some of the upgrades that are

expected to -- that will happen to the CMS detector. The

upgraded CMS detector. The MCAPS will be obliterated and have to

be replaced and that will be replaced by a hadron calorimeter.

There are upgrades to the pixel detectors. They will replace the

muon system and they can detect muons at low scatter angles.

The beam pipe is closer to the interaction point. This will

make the pixels closer to the interaction point. And, of course,

there will be readout electronics that will be upgraded for the

hadron calorimeter.

This is just a snapshot of the updates. I wanted to give a

quick summary of the detector upgrades expected.

For ATLAS, there will be new muon chambers and the tracking

detector will go up to 4. And high granularity timing detectors

will be installed. And there will be upgraded trigger and data

acquisition system. This is an improved high-level triggers and

of course, electronics update such as associated with the liquid

argon calorimeter and tile calorimeter and so on.

This is a quick snapshot of the upgrades.

Now let me go to the outline of my talk and the results that

I'm going to show today.

I wanted to find a way to put all of these results in

perspective. The way I came up with is to categorize them in

terms of analyses that target precision and analyses that include

interesting ways of dealing with background suppression, so novel

machine learning based methodology.

That gets a lightbulb and precision is a dart.

If analysis doesn't enter these categories, that doesn't

mean anything, it's just the scheme I came up with. I'm going to

follow this and go over each decay mode and talk a little bit

about nonstandard model Higgs bosons.

Higgs to ZZ to 4L. This is an example of an analysis where

we will be able to increase the precision of measurements and be

able to measure the Higgs mass to a greater precision. And you

can see that it's, there's a sizable systemic component that some

of which is associated with the mass resolution and the lepton

identification uncertainty. And, of course, we will be able to set

width within this channel. And you can see the -- that settles

at 125.38 with the uncertainties that are shown here. The stat

only uncertainty is in the red curve and systemic statistics is

in the black curve. These will give similar or almost the same

but it's still important to understand these systemic

uncertainties associated with the mass resolution and lepton

identification.

Going to Higgs to gamma gamma, this is in the realm of

precision. We will be able to reduce the uncertainty by a factor

of three compared to current measurements and some of the reasons

we will be able to do this is as follows. A limit of 10

luminosity. The HGCAL, the improved tracker and lower material

budget. And pileup suppression and timing detectors. And new

algorithms will be implemented and those are expected to

contribute to the reduced uncertainty.

If you look at the contributors of the systemic uncertainty,

they are mostly from residual Pt dependence of the photon

electron energy scales and there is some uncertainty arising from

the modeling of the material budget. Here is best fit value,

125.38 and you can see in this particular case, it will be

important to start reducing some of the, some of these sources of

statistical -- systemic uncertainty.

We really nail down these uncertainties to get a more

precise value of the mass.

Let's look at Higgs to tau tau. Again, this is also in the

realm of precision. This is a really interesting study done by

the ATLAS collaboration. These are the signal strengths

presented in terms of the template cross section framework. The

Higgs to tau tau was studied for each of the Higgs production

modes and the most precise production mode is the vector boson

fusion topology with about 7 percent uncertainty associated with

this measurement.

And these uncertainties, the residual uncertainties are

theoretical of the signal and there are some uncertainties

associated with the hadronic tau decays and identifying hadronic

taus essentially.

Moving onto using the Higgs to tau lepton decay, this

particular channel to look for to say something about the CP

state of the Higgs.

As you know the standard model Higgs is even under charge

parity conversion and any deviation from this state indicates new

physics. This is a nice way to look for new physics and of

course within this framework, one can define alpha, H tau tau.

That's a ratio of the signal modifiers given at the Lagrangian.

For pure scalar the alpha is 0 and pseudoscalar it's 90.

And so one can compute this alpha based on this delta, phi

CP angle which is the angle between the decay planes of the two

leptons there. Is a non-trigger relationship between alpha and

phi CP. This is how your experimentally determine alpha and one

can then quantify this alpha to make a statement about the state

of the Higgs.

Moving onto Higgs 2 mu mu. This mode has a low blanching

fraction. This mode was observed with the 3.0 significance in

Run2 because of the excellent muon momentum resolution of the CMS

detector.

Going to HL-LHC, we can improve the performance and a lot

will come because of the eta acceptance. This is going to be to

about 10 percent increase in the signal acceptance and the mass

resolution is also expected to improve by about 30 percent.

You can see here the uncertainties on the modified signal

strength. Or the signal strength modified I should say. What is

interesting is that with just a bit of the HL-LHC data, we should

be able to really claim discovery or first observation of H mu

mu. This is a channel to watch out for and this is where we will

start studying in the precision realm.

For these kinds of analyses, we benefit from intelligent

neural network-based background suppression.

For analyses that are just productions I have this projector

here and there are some that are Delphes based. So do indicate

that. But for the most part all are projection based. So I

wanted to point that out.

Moving to Hbb. Precision analysis in the precision realm.

This is at Run2, let's look at what Hbb looked like. The HHbb

was observed with 5.3 sigma significance. And HL-LHC, the signal

strengths, we're going to be in a regime where we're dominated by

systemic uncertainties.

This is the simplified template cross section for different

channels and mostly what the sensitivity comes from the boosted

regime because that's how you can suppress some of the

backgrounds.

And just to say, the residual uncertainties, the systemic

uncertainties really arise from theoretical and modeling

uncertainties and there are some experimental uncertainties that

do arise from flavor tagging. I'm highlighting these just so we

can target what are the uncertainties to nail down as we move

towards the HL-LHC era.

Higgs to CC. This is also, this was a simultaneous

measurement done by the ATLAS collaboration projected to 3,000

inverse femptobarn. This is the same final state that was on the

previous slide. This is Higgs produced in association with the

vector boson. There are several decay channels that one can come

up with. This is two leptons and measure the signal strengths in

each of those. And although this is not, it's going to be hard

to nail down H to CC. This is the expected significance is 6.4

times the standard model. I want to say the Run2 analyses from

which these projections are made is a very beautiful analysis

where Z to CC was identified for the first time. It's absolutely

phenomenal analysis. And I think that we are already doing very

well at Run2. I would say the projections are a little more on

the conservative side and hopefully with better tagging we can

possibly do better than this. I wouldn't say this is negative.

Also, given we can do more with H to CC. Like I said,

advanced tagging algorithms like particle net and so on are being

used for Run2 already. We hope to get better versions of these

taggers and really try to nail down some of the uncertainties

arising from this misidentification.

And this result can be interpreted in terms of the kappa

framework which is a modifier that you can see here and this is,

of course, the signal strength.

The Higgs and the top. This is where I'm getting towards

the end. I have a few analyses I want to talk about and go to

diHiggs and close it.

The evidence for TTH, to HBB is 3.9.

This is evidence of one -- this is an event display of one

of the TTH events from Run2 with a very interesting event here.

And I picked this mostly because it lights up the whole detector.

For the projection analysis, it was mostly done for a Higgs to BB

decay. And for this analysis, one also gains from the use of

deep neural network based on discriminators to suppress TT and TT

plus BB background. That is why this gets one of those idea

bulbs.

The discovery with dilepton is possible with 1/3 of the

HL-LHC integrated luminosity. The signal strengths are close to

one and we can possibly study this in the realm of precision

physics.

In this particular analysis, it was mostly projection based

but there were some acceptance taking from a -- based analysis

that provides numbers with the 200 factored in.

Going in the same theme, this is TTHH. This is a very

difficult process to study because you can see the cross section

is .0948 femptobarn. The topology, this is interesting because

of the multiplicity of final state objects this. Is H to BB and

top to WB and the W decays to L nu and QQ.

So there are many final state objects. In this particular

analysis, the deep neural network base was used to separate the

signal from the background.

A lot of the systemic uncertainties are associated with the

jet energy scale because of the number of jets in the final state

resolution and also B tagging.

So it will be good to nail down some of these uncertainties

going forward.

The combined production of TTZZ replacing one Z with an H

progressively is about.84 times the standard model. But this is

just a very hard process to isolate. TTHH goes to TZH. So one

of the processes with the Higgs, this can be potentially found at

the HL-LHC but it's going to be challenging to find TTH because

it's a hard problem and very few variables exist that allow one

to distinguish this topology from a ZH, TTH. It will be nice to

take on this challenge and see if we can isolate TTHH.

Moving onto diHiggs now. This would also be, this is a

Delphes based analysis and that implies 200 pile up assumptions.

This is HH where H goes to WW and H goes to gamma gamma and H to

tau tau and H to gamma gamma. And the events are categorized

based on the number of leptons after a diphoton pair is

identified.

This is the kind of analysis where one benefits from deep

neural networks to suppress backgrounds and the uncertainty, the

sources of uncertainty on the jet ET scale, the mass resolution,

PDF and alpha associated with the Higgs production modes, so yes.

This expected, this is not a very -- this is not going to be one

of the most sensitive channels. The sensitivity is expected at

.2 sigma. I will show the other more sensitive channels but it's

still interesting to look at and it would be nice to add the

channel like this to the other channels to claim the diHiggs.

So looking at, continuing on the diHiggs vein. This is HBB.

Now you're getting to see a larger branching fraction here to

gamma gamma and here the expected significance is 2.16 sigma.

This is the N gamma gamma distribution and BB distribution. And

this category 4 here refers to a cut on a neural network

discriminator that is the most efficient to pick out signal and

suppress background. Other cuts were also explored in this

adult.

But, yes, this is the one that was most efficient at

reducing the backgrounds.

And so now let's go to the most sensitive diHiggs channel

which is HHBB, and HHB gamma gamma. Adding the two. A lot of

the uncertainty arises from photon efficiency and B and C tagging

efficiency. The expected significance is 4.6 without systemic

uncertainty and with it's 3.2 sigma.

One can interpret these results in terms of the kappa

modifying parameter. You can see the standard model value is

here and the 3 and 5 sigma lines are here.

Actually, the observation of this process, so you can see

without the systemic uncertainty, it really is close to 4.6 sigma

but the assumptions do degrade the performance. But yes, it

would be nice to see if some of these systemic uncertainties can

be tackled and they arise mostly from the photon efficiency and B

and C tagging efficiency.

So then I want to quickly talk a little about the rare Higgs

boson or the search for nonstandard model Higgs boson. This is

an interesting analysis search for rare Higgs bosons with Mesons.

This is Higgs to J psi and Higgs to epsilon.

In these final states one can construct an analysis that is

almost background free and the sensitivity is proportional toll

the luminosity and one can use this very clean channels to set

limits on the branching fractions associated with these

nonstandard Higgs boson decay modes.

And the final analysis that I want to cover is the search

for high mass resonances. So this is H to WW but this H is not a

standard model Higgs. The mass change can vary from 115 to 5

TeV. This is an analysis where the leptonic modes were

considered.

And this is also an analysis where one gains from the use of

a deep neural network to tackle some of the backgrounds and so

this DNN, this deep neural network was trained with kinematic

variables and they were standard like PT and mass of the

dileptons and so on.

You can see the distribution of this DNN in Run2 analysis.

This is a projection from the Run2 analysis. You can see it's a

hard problem to solve. This is the output of the deep neural

network discriminant in terms of the transverse mass which is

close to -- which is an interesting variable to use.

And like I said, it's kind of obvious this is a hard problem

to solve. One can still interpret these results into terms of

MSSM and in the plain -- beta and A. The values of this

particular analysis is sensitive to low values of [inaudible] and

tan beta.

With that, this brings me to the conclusion. I showed

several new projections for the HL-LHC and I split the analysis

in terms of those that compute the Higgs mass, width and

coupling. There will be several analyses where machine learning

methods are really going to be paramount to suppress backgrounds

and they will provide access to priestly unexplored processes.

It's imperative we continue our path to using more and more

sophisticated ways of background suppression.

We do have a white paper that is published and available at

this link here. And yes, dare I say, the future is bright and

it's precise. Thank you for your attention.

[Applause]

>> Thank you. Are there questions in the room for

Saptaparna? On Zoom?

All right. Christophe?

>> Hello. I was wondering whether you have looked at the

associated production with the pairs of B Quarks, BBH?

>> Yes. It's this one, I think I went a little too fast.

Associated production. Yes, that is the primary -- this one,

right?

>> No that's a decay. Just associated production, TTH and

BBH.

>> Oh. Yes.

>> That will give you access to CP violation in the B

couplings, right?

>> Right. Yes. So I think there is a Run2 analysis that is

going to look into the -- sorry, it's HBB, right?

>> Yes.

>> So yes, I think there are people that are already

interested in looking at that but I have not seen any projections

for it.

>> Okay. Thanks.

>> Yep.

>> Great. So maybe we can thank again Saptaparna.

Since you're online, you're the next speaker?

>> Indeed. Now you should see my screen, right.

>> Yes. Thank you.

>> Okay. Thanks for the invitation to report about Higgs

physics at FCC-ee. Since you're listening to me, you will agree

that Higgs discovery ten years ago was a great success.

And it has important implications for different areas of

physics and beyond. But the real question is, are we done? Is

our mission accomplished? What is next? Next time people used

this logo mission accomplished used by Jorge W bush in May 2003

and that was only the beginning of the end.

We see the need to continue. We need to do it and now my

task is to tell you how we can do it and what can be learned.

So of course, we are discussing about various Higgs factory

and the real question what is the best one? There is no clear

answer. That is why we're discussing. There is no clear answer

because it depends a lot about what the new physics will be.

And in any case, as a decision, a choice, is a del Kate

balance between various factors.

Nonetheless, say high energy physicists, at least in Europe,

agree that the best way to reach the energy frontier is indeed to

start with an e Higgs factory. And then the last question to

be answered is whether linear or circular geometry. Both of

those options clearly have advantages and also some

inconvenience.

If I try to summarize quickly, linear machines are good

because you can easily extend them in energy. And also, you can

easily polarize the beams.

On the other hand, if you're losing circular machine, you

can reach higher luminosity in several interaction poles and it's

easy to have a dedicated Z-pole with high luminosity.

So the question that I would like to address is what is the

impact of the Z-pole measurement and whether or not the low

energy is a limitation for Higgs physics. And then maybe we will

cover the benefits of beam polarization.

So several people in the U.S. have already came up with

various directions that need to be thought of to help a little

bit in the discussion and the choice between the different

machines.

For what concerns the physics, clearly there is various

important points that the Higgs factory should achieve. You want

precise Higgs measurement to the various standard model particle.

You also want to achieve the measurement of the Higgs coupling

and have access to rare and exotic decays. And be able to

measure the electroweak and the -- couplings. You want to

improve the sensitivity of the input parameters of the standard

model starting with alpha S.

And you also want to have a direct and indirect discovery

for new physics.

Those are all important considerations before when we're

looking at the various energy threshold which you will achieve,

there is various ones. There is the production of ZZ, there is

production of pairs of electroweak gauge boson and what is

important for each factory, it is the production of the Higgs in

association with the Zh boson and you want to go to higher energy

to produce pairs of top Quark. And later on you want to produce

in association with pairs of top Quark and reach double Higgs

threshold.

And clearly, if you now see the evolution of the luminosity

as a function of the energy and the center of mass for the

various machines, you will quickly understand that the low energy

regime is -- circular e machine. If you want to go to higher

energy, you need to rely on the linear e electron, e

machine or you want to use a muon or even using a circular proton

proton machine.

So keeping this fresh in mind. What is the run plan for

FCC-ee. We're planning a run at the Z pole, something like 4

years where we accumulate 150ab.

And this will be run at the W threshold. 2 years to

accumulate 12 in the atto barn. And then a Higgs threshold that

will take three years to accumulate. And then you will be able

to expand the machine to reach a ttbar threshold and accumulate

1.5 femptobarn.

The order of this is not totally decided yet. You will

still be subject to optimization.

The data will be accumulated in the first 3 minutes of the

physics program of this machine. And then there will be exciting

programs with different priorities every year. It goes very

quickly to go from the Z to the WW to the Higgs threshold.

So that's really exciting because you can really review very

quickly your physics.

So clearly you will achieve sue push statistics in only 15

years of the physics program. Just to give you some numbers, you

will accumulate 10 to the 12Z boson. 10 to the 8W pairs,

et cetera, et cetera.

Just to give you some perspective, you will be producing

100,000Z boson every second and 10 to the 4W every hour and 1500

Higgs a day and 1500 top a day.

You will achieve great physics if you're able to control all

your systemics.

So very quickly, we have these three important thresholds,

the Z, the WW, the Higgs threshold and the ttbar threshold.

And this will design the physics program of FCC-ee. We have

the intensity frontier and then you will have all the physics

associated to the Higgs where you will be measuring with great

accuracy the mass of the Higgs and the couplings and as well as

the Higgs self-coupling.

And finally with the run of the ttbar, we measure the top

mass, the width of the top and all the electroweak top couplings.

Let me maybe discuss a bit further this because it's

important also. They cover all the other important physics

considerations that were mentioned before.

You will be achieving great electroweak and QCD measurement,

the mass of the Z weight, effective neutrino numbers,

asymmetries, et cetera.

You will be also measuring alpha, alpha strong with

[inaudible] accuracy and studying the Quark fragmentation and

clean and non-perturbative QCD.

The energy frontier allows you to do direct searches of

light, new physics, axion like, dark photons, heavy neutral (ph)

leptons, et cetera.

We will produce something like 10 to the 12 bbBar or CC bar

pairs. 10 to the 1 pairs of tau leptons. You will be achieving

great physics measurement, the CKD measurements and probing all

the models that are flavor by flavor anomalies and you will be

achieving nice top physics like electric precision measurement

using the -- or looking at lepton universality violation.

And all these things come with important detector

requirements. Starting with vertexing, tagging, energy

resolution, hadron identification. A good momentum resolution

tracker, else, et cetera.

The talk is devoted to the Higgs. I should say you should

really have a very important requirement on the hadronic

resolution and the tracking and that is vertexing. I give you

some characteristics here that will be important to really

achieve the measurement that are expected.

So now, let me come back again to the various physics

considerations. You can see that basically the FCC-ee program

really complete almost all of these important considerations.

Very quickly, I want to mention this discovery potential,

indirect discovery potential by the electroweak precision

measurement. You can search for the stop in a region that is not

covered by the direct search for the stop at the LHC. This is a

bond you obtain by the measurement of the Higgs coupling.

And also looking at heavy neutral Higgs. There is really

some region of parameter space that will be what you can do at

high luminosity phase of the LHC and what you can do at directly

at FCC-hh. That is here, you will do better. But you know, the

direct search is at high luminosity phase of the LHC will be less

sensitive in these particular regions of the parameter space.

And you will also be using electroweak precision measurement

to indirectly search for new physics and areas of -- that you can

really reach by this measurement at FCC-ee.

You can also use all the -- frontier measurement to directly

search for new physics in the case of long-lived particles or

searching for axion light particles. There is a decay of

80mesonss or producing the -- by decay of the Z or the Higgs

boson before you can see here a release of parameter space that

is complementary. From the constraint that you will observe from

astrophysics and cosmology. That gives you the best bet for

long-lived AL Ps. But for short lived, you need a collider and

FCC-ee is one of the best machines to search and put some

constraint on this short-lived axon like particle.

You can use the Z boson and Z decay to probe the [inaudible]

that could be at the origin of the masses of the neutrino and

that can explain this asymmetry of matter and antimatter and the

lek to genesis model.

The region of space covered here by FCC-ee is the one that

is really probing the leptogenesis model in large parameter

space.

Again, let me come back to the Higgs physics program. It's

important to really understand the Higgs program will benefit

from the Higgs -- processes at 240 or 250 GeV. We will produce

is million boson. You will obtain complementary information from

the WW fusion production at 365 GeV. At the threshold of TTB.

You will produce fewer Higgs boson but this additional Higgs

boson that we come with important information.

This can be directly observed by looking at the sensitivity

of the various Higgs coupling when you consider only the run at

240 GeV here in light blue. And when you also gain the

sensitivity when you add the run at 360 GeV. You see that this

additional run at 365 GeV is particularly important when it comes

with the measurement to the coupling of the WW and the charm

Quark and the tau -- [inaudible]

What I want to mention is that there is also an important

complementary between FCC-ee that comes between high luminosity

and LHC. High luminosity and LHC is barely complementary to the

charm as we just learned and this hole will be complemented by

what will be, what we will learn directly at FCC-ee.

On the other hand, you will see here that clearly FCH-ee

because you cannot reach directly the TTH threshold, has no

direct access to the top -- couplings.

When you try to add the information and combine together the

information at FCC-ee together with high luminosity phase, then

you don't need to reach the TTH threshold to gain information of

the top Yukawa. Or the machine that reaches the ttbar threshold,

don't perform better than LHC for what is a top Yukawa.

There is an important synergy between the FC-ee and the high

energy -- this is a channel that is statistically limited. So

mainly the gamma gamma channel and decays to two muons. Again,

if you compare the two plots, FCC-ee alone and FCC together with

high luminosity phase of the LHC, you see now you can really

reduce significantly the error bars on the coupling to the photon

and the coupling of the muon.

And this is a synergy measurement in the sense that FCC-ee

brings additional information compared to what high luminosity

phase of the LHC does.

Let me briefly mention this complimentarity between the Z

run and Higgs run. For that you can compare the sensitivity on

the various Higgs coupling, you know, with the run, the run of

the Z pole. The top of the bar here is the sensitivity at that

pole. We rely on the electroweak precision measurement that has

been performed and finally you see what is the gain of having a

properly dedicated Z pole and you can compare to a perfect

situation where you have an infinite precision on the electroweak

precision measurement.

This is a -- of the fit. It's a plot that is a little

difficult to read. Let me zoom in. This takes the ratio of the

real electroweak precision measurement to the case of a perfect

electroweak precision measurement. And what you notice is what

is important of adding a dedicated Z pole. For the coupling of

the Higgs to say the vector boson fusion, it's almost a factor 2

improvement. You will be improving the electroweak precision

version compared to what is learned from [inaudible]

Of course, the same thing could be true with more limited

number of Zs as something that will be achieved at a linear

collider. As I said at the beginning, the linear collider

doesn't have a dedicated Z pole. So you don't accumulate 10 to

the 12Z. Nonetheless, you will reach 10 to the 9Z using the Z

relative. But then for a linear collider, 10 to the 9 is still

far away from infinite number of Z. You will still be limited by

30 percent compared to the perfect electroweak precision

measurements.

So the conclusion is 10 to the 12 is about 10 percent away

from an infinite number of Z. Where 10 to the 9 is 30 percent

away from an infinite number of Z bosons.

The other way to understand this synergy between the Z pole

and dedicated Higgs factory run is to look at the correlation of

the various couplings. And you see that there is a strong

correlation between the electroweak precision measurement and

Higgs measurement. If you're adding the dedicated Z pole at

FCC-ee, you see this relation between the electroweak precision

measurement and Higgs measurement is broken. That is why you are

not really limited any longer by the uncertainty in the

electroweak precision measurement.

So something that you can notice clearly also if you look at

the correlation between these various [inaudible].

Finally, the complementarity that exists between FCC-ee and

FCC-hh. The first example is in the measurement of the untagged

branching ratio. FCC-hh will achieve a fantastic sensitivity of

the order 10 to the minus 4 in the invisible branching ratio.

On the other hand, I mean you cannot get an absolute

measurement of the width. You cannot basically merge the

untagged branching ratio. For that we need FCC-ee. You really

have access to the total width of the Higgs.

The other example important example of this complement tarty

is in the measurement of the top Yukawa couplings. FCC-hh claims

to have superb sensitivity. In the ratio, a lot of uncertainty

drops. You can notice in this table.

But then if you want to extract the Yukawa copy from the

measurement, you need to know the TTZ. This is precisely where

the FCC-ee entries. Notice here the sensitivity in the

measurement of the top Yukawa coupling with and without FCC-ee

and you see if you want to achieve this sensitivity on the top

Yukawa couplings, then you also need the FCC run to know --

electroweak top couplings.

Then why is this top Yukawa coupling important? It plays a

crucial role in the determination of the Higgs self-coupling at

FCC-hh with the measurement of the double Higgs production. A

one percent sensitive on the top Yukawa couplings brings you

5 percent uncertainty in the determination of the Higgs

self-couplings.

Without the FCC-ee, that aloe you to reach one percent

sensitivity on the top Yukawa but you can't claim you reached

5 percent on the determination of the Higgs self-couplings.

I think I don't have much time left. I want to mention also

some new studies that are going ton. For instance, in the

determination of the strange Yukawa couplings, these can be

achieved thanks to the high statistics that you will accumulate

at FC-ee and also thanks to the nice detector performance in

particular this strange tagging that is really studied very

carefully at the moment.

There is also the possibility that is unique among all the

colliders that we're discussing to have access to the electron

Yukawa. At the moment we have a bound on the electron Yukawa on

the order of 260 times the value of the standard model.

But actually, you will be able to run FCC-ee on the Higgs

pole, right, on the Z Higgs pole to really produce Higgs as an

S-channel resonance and you will have an, even taking into

account the beam spread or whatever, you will have enough

statistics to gain sensitivity to the Higgs and produce enough

Higgs boson in this S-channel mode.

It's not enough to produce the Higgs, you need to see the

Higgs: You need to be able to distinguish this Higgs from the

off-shell Z. And for that it's better to look at decays into

particle that don't couple to the Z directly.

You will be looking at the Higgs decays into gluino and with

careful statistics, you will accumulate something like one sigma

with ten inverse atto barn.

And you run FCC for two years, for three years with four

interaction points you will reach enough statistics to be able to

claim a five sigma discovery of this Yukawa electron couplings.

Also, want to mention quickly the ability to gain

sensitivity on the Higgs self-couplings without reaching the

double Higgs threshold. This can be achieved by precision

measurement of single Higgs processes because then you will be

sensitive via quantum correction to the Higgs self-coupling. For

instance, this kind of diagram. We have associated production of

the Higgs to the Z that will be sensitive to the Higgs

self-coupling. You need a sensitivity of one percent of the

determination of the cross section and this is what FCC-ee can

achieve.

The important thing is to be able to trade what is due to

the modification of the Higgs self-coupling and what is due

directly to the modification of the Higgs coupling to the Z. For

that you need to do a global analysis of the various production

and decay mode. You also need, that will be very important, you

need to run the machine at two different energies. It's not

enough to run FCC-ee at 240 GeV, you need to be able to run at

365 GeV to be able to -- the various contributions to this cross

section. To break some -- the conclusion is really that you

don't really need to reach the double Higgs threshold to be

sensitive to the Higgs self-couplings.

If you look at the sensitivity you can reach, with 4IP, you

can reach 25 percent sensitivity in the measurement of the Higgs

self-coupling and if that is the only deviation that exists away

from the standard model, you will reach sensitivity on the order

of 14 percent.

There are other directions that are not fully explored yet.

For instance, in particular what non-diagonal flavor structure.

In the standard model there is no Higgs in FCNC. When you go

beyond the standard model, the Higgs FCNC are the rule and not

the exception.

You should really pay attention to interesting flavor

structures that can be probed directly with new physics and that

approximate requires a combination with flavor data that has been

so far irrelevant because all the flavor assumption that we

analytic size, we assume a -- and flavor doesn't play a role.

There is ongoing work in the global team, in particular in

the talks that were mentioned before.

The other important direction will be in the single CPV

phase violation. There is a single source of CP violation that

is captured by this Jarlskog invariant. How many of those exist

at the dimension 6 level, the next level and the leading

correction induced by new physics and there is about 700 of them.

This parameter space is very large and basically goes to

[inaudible] and what is fascinating is all these new source of CP

violation don't come from the same collective effect that exist

with the standard model. Even though the effect might be

suppressed by the scale of new physics, the fact that it's not

necessarily suppressed by the smallness of the Quark mass or the

smallness of the -- give [inaudible] very large effect of CP

violation if you look at it properly.

Okay. So I think my time is over. There is really very

nice ongoing studies in Higgs physics FCC-ee and I can only

encourage you to join the team by subscribing to the link here.

I will stop here and thanks a lot.

>> Thank you.

First, we're way over time and we don't want to end the next

talk in the coffee break. So unless there is an urgent remark,

we should move to the next talk.

>> Christophe made a number of points about the colliders.

I can comment on many. But in the interest of time I will

comment on one.

The ability of the precision electroweak to improve the

Higgs coupling measurements, so if you look in the ILC report of

which Christophe is an author, the initials are in the table.

You achieve what you need already in the radiative return without

going to the GigaZ. Please have a look at that. You can look at

many other things, too?

>> That will be this number here, right?

>> We have Danny talking to us now about the e linear

collider. Maybe we can have more -- at the end of the talk.

Jenny, are you online?

>> Yes.

>> Okay. Sorry for the delay. We are ready when you are.

>> Okay.

Let me share my screen. Can you see that?

>> Yes. Thank you.

>> Okay. Yes, then I hope I leave you some coffee break.

But I will tell you now about the Higgs and BSM physics at the

future linear colliders.

And let's, I'm sure you know all this but maybe it's

worthwhile the take a step back and recall for ourselves what we

really want to know. And how can the Higgs boson be so light.

What is the mechanism behind the electroweak symmetry breaking

and what is dark matter made out of and so on and so forth.

We will agree that we can find answers only outside the

standard model of physics. This is also why this question of

Higgs and BSM is so strongly intertwined.

However, we're not completely clueless. What we do know is

most of the hints for BSM come out of the electroweak sector

including the Higgs. So it's very likely that some particles

must be charged under the electroweak interactions and then you

can search for them in e and use the Higgs boson as a

precision tool to study them like Christophe explained nicely.

What we don't know really is, or don't know much about is

about the participation of new particles in the strong

interaction and very importantly, we don't know the energy scale.

There is no guarantee at the moment for the direct production of

new particles regardless of what gigantic collider we build and

at what high energy.

So one needs to explore various complementary experimental

approaches.

And what is now special about the linear colliders,

obviously, the energy range which Christophe already commented

upon. So you can, they are intrinsically upgrade able in energy.

You can make them longer using the same technology or after a

couple of years with better technology or combine both by making

it longer and putting in the new parts of technology and gain

even more.

The other specific feature is the ability to provide

longitudinally polarized beams to the experiment. And some of

them only polarize the electron beam. The ILC is a bit sticking

out there but aiming for polarized positron beam. This is

important because we all know that in your beloved electroweak

interaction there is this L index of the SU2. So fermions are

chiral and thus if you have really these two beams polarized like

at the ILC, this is basically four colliders in one.

So why is this so interesting, what can we do with this?

Michael explained this very nicely on Monday and said more about

it than I can do here now. Basically, you can use it to suppress

important backgrounds. You can enhance your signal. You can use

the extra information for chiral analysis and I just want to

highlight that of course, and beyond the standard model where the

chiral structures are completely unknown. It really needs to be

determined and this can play a huge role if you want to

characterize the properties of new particles.

And finally, also, the redundancy and control of systems

where polarization helps a lot as we will see later on.

Let's start with the Higgs boson.

Here is a plot which you probably have seen before with

e cross section for Higgs plus anything versus the center of

mass energy and when people talk about the Higgs factory, they

really aim at this little yellow peak here. Namely the Higgs --

peak at 250 GeV. But there is much much more. Above 350 GeV,

about the single Higgs production and fusion becomes interesting.

But then more importantly, above 500 GeV, TTH production and

double Higgs [inaudible] kicks in.

And even higher energies you can produce double Higgs. To

really do the full Higgs program, you need more than just 250

GeV. And as Christophe said, in particular the top Yukawa and

the Higgs self-coupling stick out there.

Still, why are people talking about 250 GeV all the time?

Because there is really one key measurement which profits from

exactly this process by using the known and four momentum of the

initial state and the easily reconstructible forward momentum of

the Z boson and one can reconstruct the Higgs without looking at

the decay products.

This is the most model-independent way you can possibly

measure really the total Higgs cross section when you get then an

absolute normalization to determine couplings and not just signal

strength or ratios of couplings and so on.

This enables a plethora of precision measurements including

the CP properties of Higgs fermion couplings and ZH couplings and

on and on and the kinds of branching ratios from Higgs to

invisible and so on and the list you can find in the

corresponding white papers.

Just to show you, I mean here I basically wanted to remind

you that the linear collider physics studies are all done in

full -- detector simulation like this one here. The detector

performance gauged really against prototypes which interest. So

this is usually quite reliable what comes out of these studies.

So polarization and the Higgs couplings, Christophe showed

us a big comparison plot but maybe it's worthwhile to look on

what polarization has to do with Higgs couplings and especially

with this key process of HiggsStrahlung. The left right of

higgsstrahlung allows us to disentangle different SMEFT

operators. You have these two diagrams here and one flips the

sign when you reverse the spin and the other keeps the sign.

Measuring the left right asymmetry lifts the degeneracy between

the operators.

And that leads to this now well known fact that at the end

of the day, a circular collider plans to accumulate more

luminosity at 250 GeV but without polarization, you get at the

end of the day to very, very comparable estimates on all the

individual coupling projections.

If we look here at the red and the green bars and then it

depends a bit on how optimistic or pessimistic you are on these

S1 and S2 scenarios on systemics and so on.

Here the bottom line is all proposed machines can deliver

the 250 GeV Higgs program. So this is really not a place where

one should bicker about which machine we get.

Then of course we want to talk about high energies. What

happens now if you look at the evolution with energy and here now

you see in green the 250 GeV blue adding 500 and red 1 TeV.

(captioning time expired.)