What will we learn about the Higgs boson from future colliders ?

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Over the past two week, you have absorbed a huge amount of information about the Higgs boson.

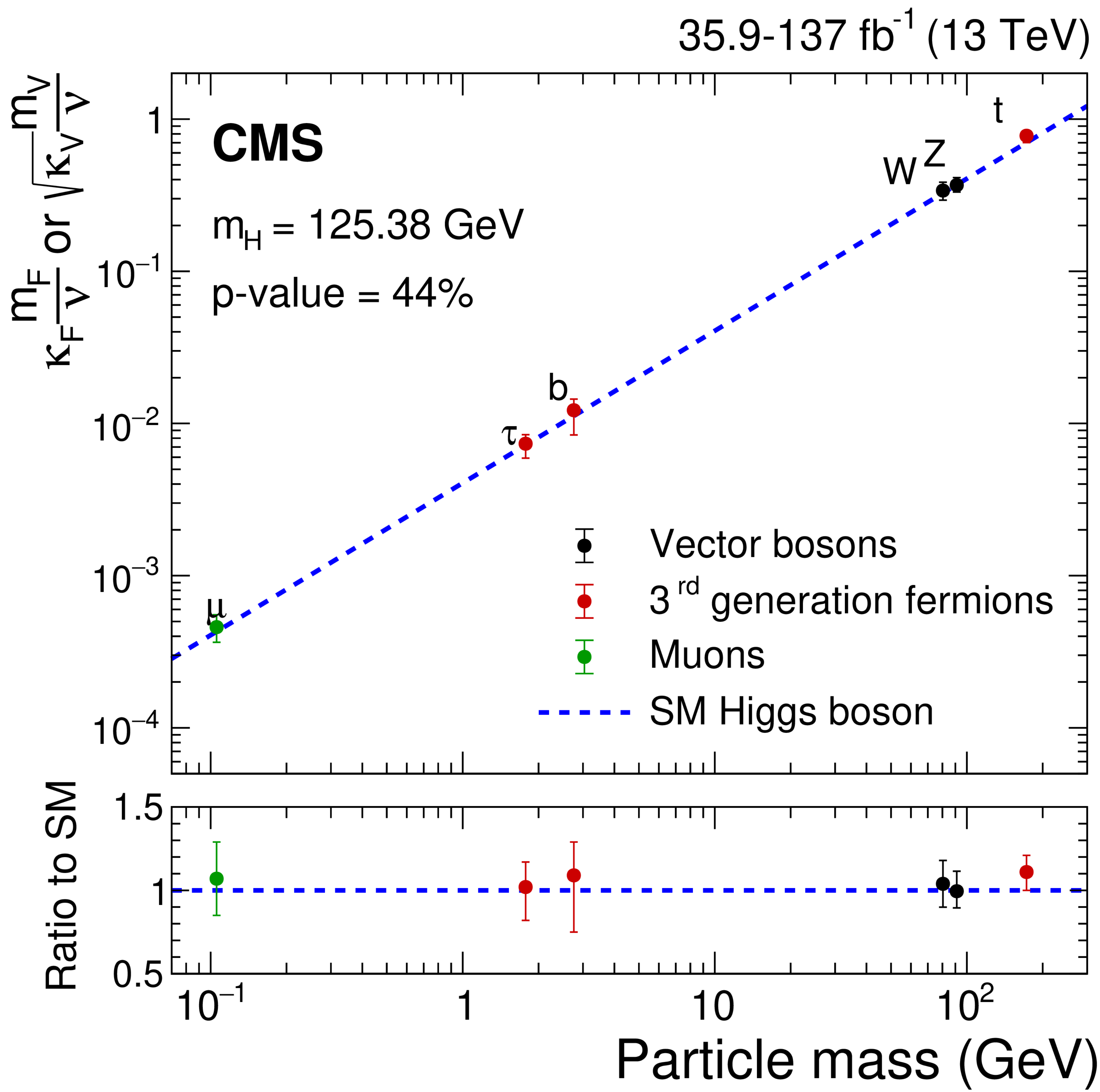
Probably there is not room in your brains for much more.

So this talk will be light on new information and will emphasize instead a point of view on how to think about what you have learned.

Let me first emphasize the main thing that you have learned from the speakers at this institute.

The Higgs boson is still a new elementary particle, discovered only 9 years ago. But we now know a large amount about it properties.

In particular, we now have strong evidence that the Higgs field is indeed the sole source of mass for the known elementary particles.



35.9-137 fb^{-1} (13 TeV)
CMS
m_H = 125.38 GeV
p-value = 44%
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
t
W
Z
b
τ
μ
Vector bosons
3 rd generation fermions
Muons
SM Higgs boson
Ratio to SM
Particle mass (GeV)

The Standard Model is surprisingly attractive as a final theory of elementary particles.

The Standard Model Lagrangian is the most general renormalizable Lagrangian with the gauge symmetry SU(2)xU(1) and the known particle content. That is, writing out all of the possible terms and then simplifying with appropriate changes of variables, we can reduce any such Lagrangian to the form

$$\mathcal{L} = -\frac{1}{4}\sum_a (F^a_{\mu\nu})^2 + m_W^2 W^+_\mu W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu$$
$$+ \sum_f \overline{\Psi}_f (i\gamma \cdot D_f - m_f)\Psi_f + \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

with, also, $m \to m(1 + h/v)$. This depends on there being only Higgs doublet field.

Unlike previous proposals for the theory of particle interactions (Fermi theory, chiral Lagrangians, models with no charm quark or no top quark, etc.), the Standard Model can be extended to higher energy with no clear limit (up to the Planck scale).

It is very tempting to say, “This is the theory of everything. We are done. All that remains is to stress-test the theory with higher precision measurements.”

I would like to persuade you not to accept this point of view.

The Standard Model is very good at parametrizing the physics we see.

It is very poor at explaining why.

Why do the quarks and leptons have the masses we see ?

Why is CP violated ?

Why is there mass at all ? Why is the gauge symmetry broken ?

The SM does not explain the why of Higgs symmetry breaking, a major phase transition in the early universe.

Many theorists are happy with the statement, “We postulate a scalar field and assume that its potential has a minimum away from $\Phi = 0$.”

This ignores many examples from condensed matter physics in which the presence of a broken symmetry state has a beautiful physics explanation:

magnetism, superconductivity, liquid crystals, …

If SU(2)xU(1) symmetry breaking has such an explanation, it must depend on new particles and forces outside the SM. We have the opportunity to find those new particles and forces, if only we don’t give up.

The example of superconductivity is particularly close to that of the SM.

The Landau-Ginzburg theory postulates a complex scalar field that exists inside a metal. This field acquires a thermodynamic nonzero expectation value. From that description, with only a few parameters, we explain:

- the thermodynamics of the phase transition
- the critical current
- the Meissner effect
- the Abrikosov vortex state (superconducting magnets)
- the presence of Type I and Type II superconductors

However, this was a purely phenomenological description. To answer the why question, took further insights by Bardeen, Cooper, and Schrieffer.

It is worth studying these condensed matter systems.

Many theorists are focused only the “gauge hierarchy problem”: why is $m_h \ll m_{Pl}$?

In his mind-blowing lecture, Nathaniel Craig gave us 22 solutions to this problem. But most of these do not address the real why question: Why is SU(2)xU(1) broken in the first place ?

For those that do (supersymmetry, global symmetry, Randall-Sundrum, conformal symmetry), there are many more fascinating details that you need to study, some of which lead to experimental observables.

The Standard Model is a similar "phenomenological effective theory". We don't know what lies behind it.

How is the low-energy Higgs field related to more fundamental Higgs fields ?

Is it one of large multiplet of scalar fields ?

Is it a mixture of fields (maybe one for each generation) ?

Is it a composite of more fundamental scalars, fermions, or superpartners ?

Is it a component of a gauge field, in universe with small extra dimensions ?

We need to answer these questions to address all other open question of particle physics.

How can we understand how the Higgs field couples to fermions, to explain the mass spectrum and CP violation, before we know what this Higgs is made of ?

Dark matter may not be a manifestation of the Higgs sector, but it is in many models.

According to SU(2)xU(1), neutrinos ultimately get their masses from the Higgs boson. So even here, we cannot escape the Higgs field's mysteries.

How can we address these questions experimentally ?

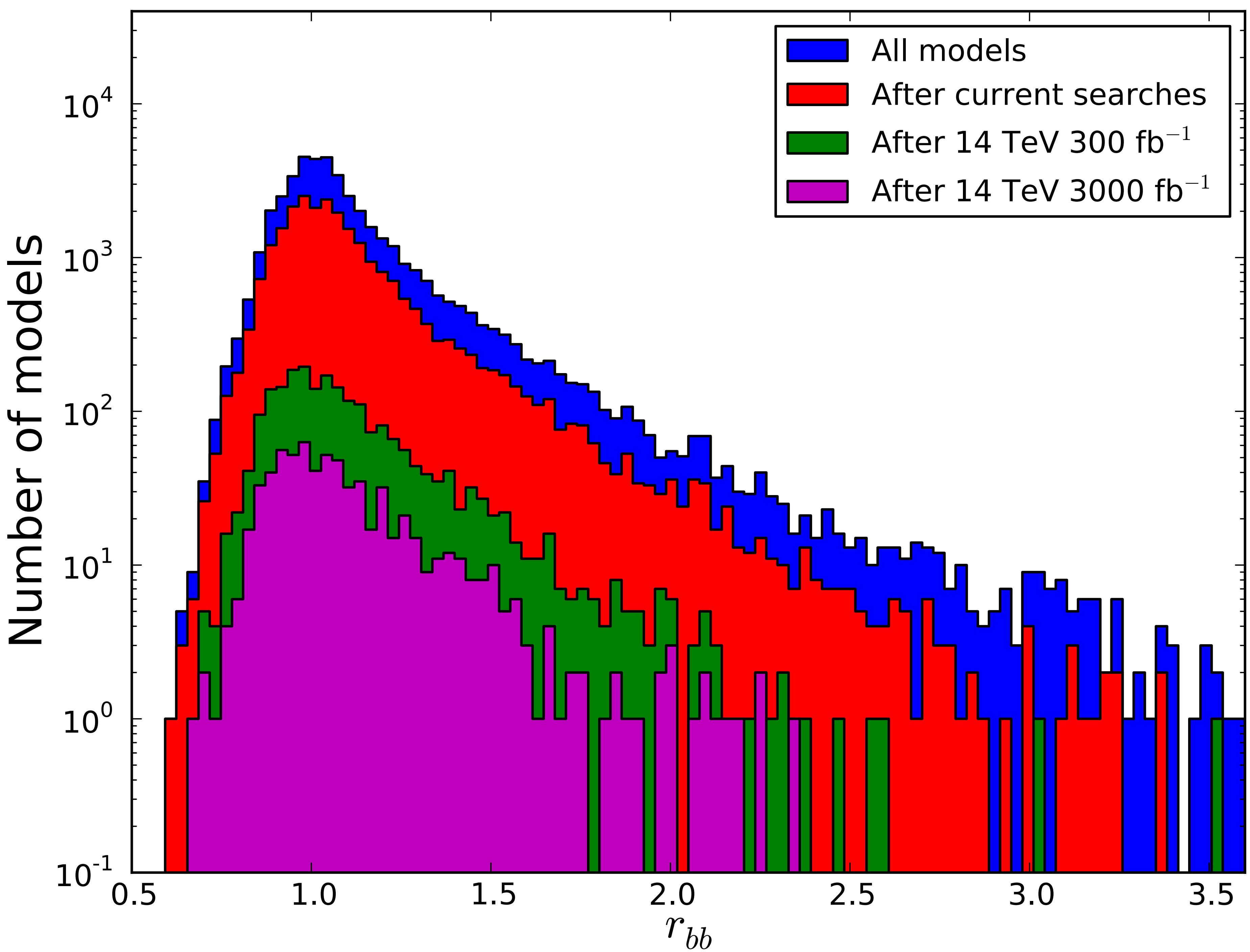
One way is to discover the new heavy particles.

This was the goal of the LHC. There is still an opportunity. Especially, if these new particles have only electroweak couplings, the HL-LHC will extend the reach in mass by almost a factor of 2.

Here, I will stress another probe, the precision study of the Higgs boson. This method has a similar reach in mass. But it is not competing, it is complementary. The models that have accessible new particles and those with large SM corrections are, in general, distinct.

Thus, precision measurements open a new window that we have not looked through yet.

Example of SUSY: There can be precision effects from b squarks at 4-5 TeV, well beyond the reach of LHC.

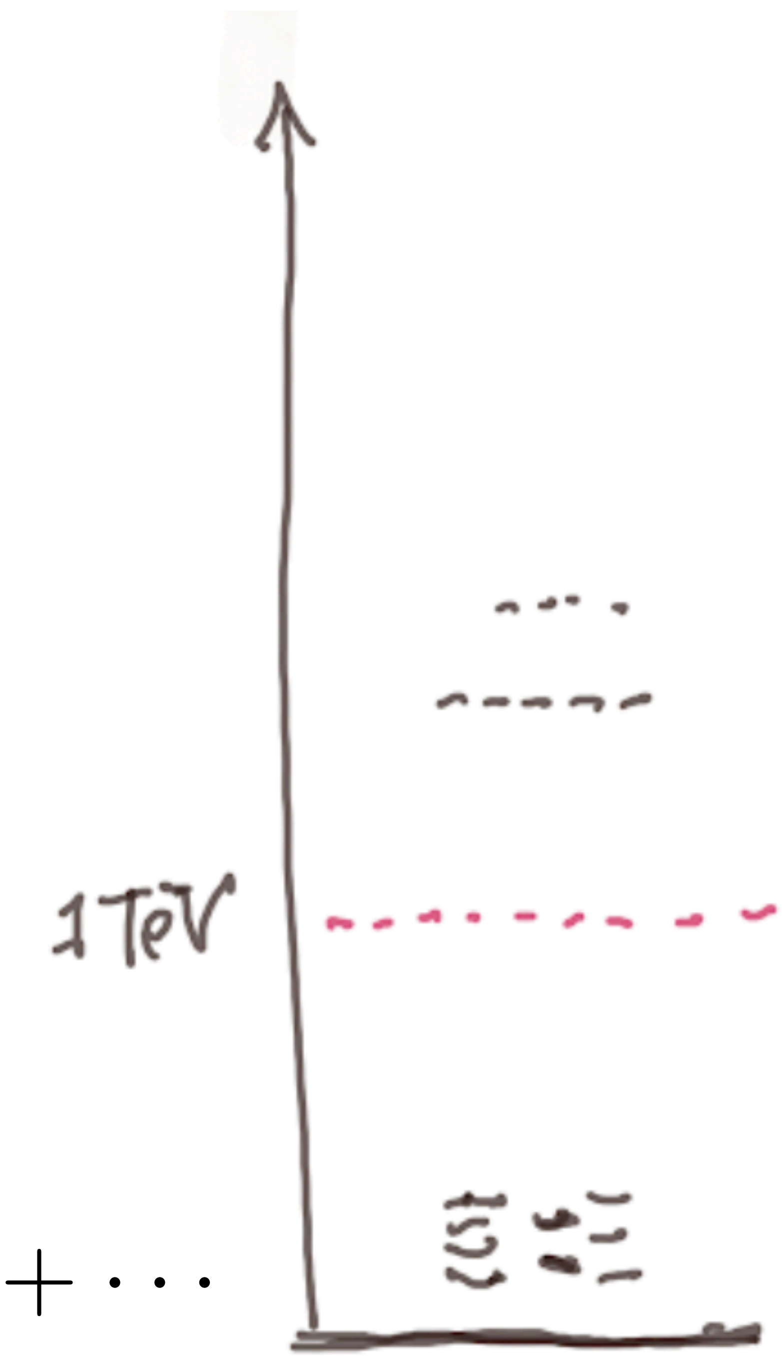


Cahill-Rowley, Hewett, Ismail, Rizzo

Today, there seems to be a gap in mass between the known particles and hypothetical higher mass particles.

What particles have masses below the red line ? Are they just the SM particles, with one Higgs boson ?

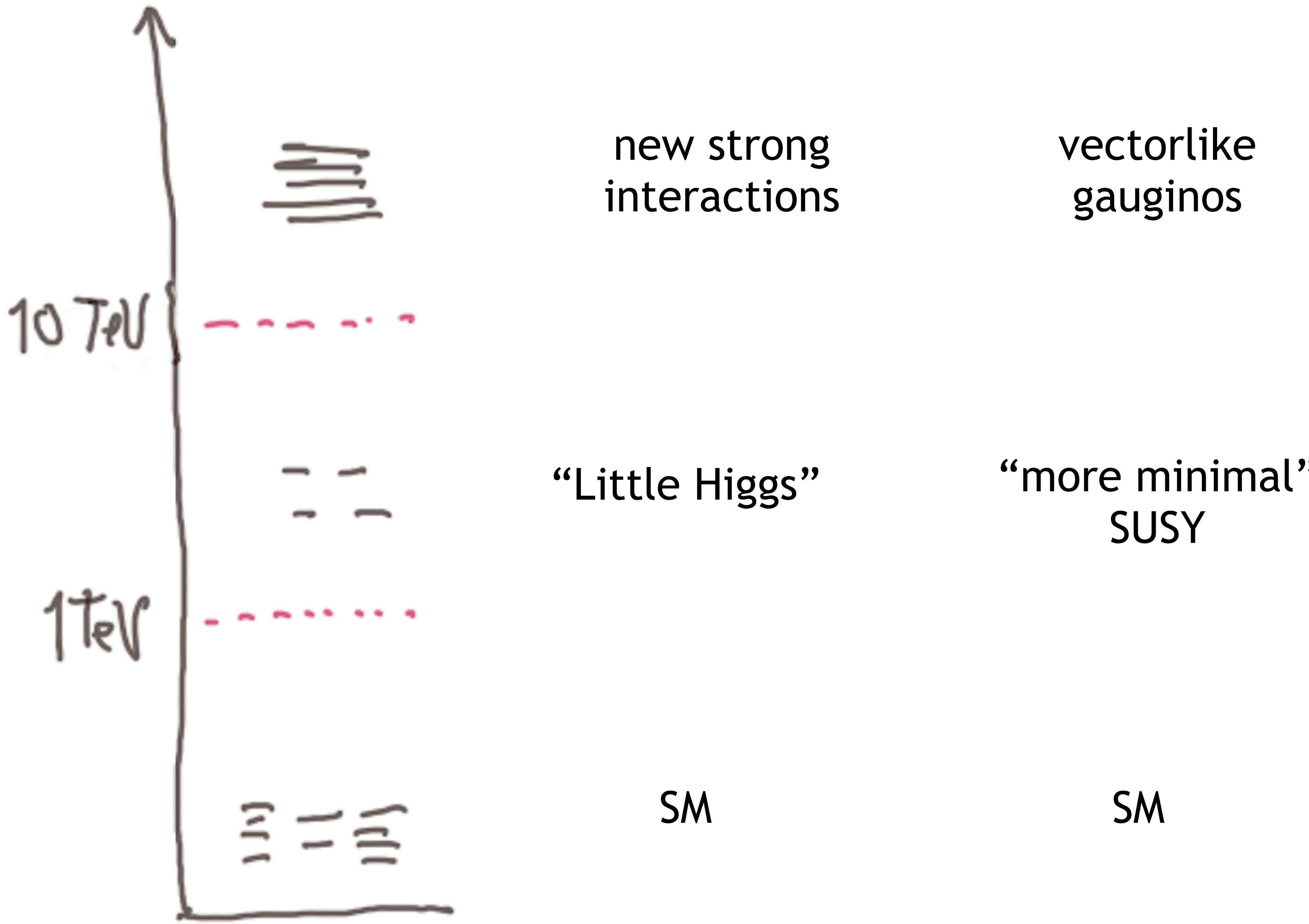
If so, we can “integrate out” the effects of the high mass particles. This gives the “Standard Model Effective Field Theory” (SMEFT), as described by Veronica Sanz. We find



$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2}\mathcal{O}_i + \sum_j \frac{d_i}{M^4}\mathcal{O}_j + \cdots$$

dimension 6 dimension 8 ...

Models that explain the gap between the 100 GeV scale and the scale M often have even a more complex structure:



Eventually, we must explore multi-10-TeV. I'll discuss those accelerators later.

In the SMEFT, the effects of BSM physics are necessarily small. They are of order

$$v^2/M^2$$

where $v = \langle \Phi \rangle$. These are effects at the few-percent level.

However, if we can reach this level, the c_i coefficients can show many different patterns.

By discovering the c_i and distinguishing these patterns, we can learn about the higher-mass-scale theory.

This situation is very similar to that in astronomy with the Cosmic Microwave Background. There, until you can measure the non-uniformity to the 10^{-5} level, you cannot learn anything about cosmology. Once you reach that level, you can measure the cosmological parameters.

For Higgs, the goal from theory is the % level. With the beautiful experimental techniques described by Maria Cepeda, we may get there already at HL-LHC. However, to prove violation of the SM and to see the pattern, we will need even more accurate measurements, below the 1% level.

We are lucky that, even in the SM model, the Higgs boson has many decay models (10 modes with $BR > 10^{-4}$). Each probes for a different type of new physics:

W,Z decays: Higgs singlets, Higgs as a Goldstone
fermion decays: 2-Higgs doublet models
gluon decays: vectorlike top quarks
$\gamma\gamma$, $Z\gamma$ decays: all heavy vectorlike states
c,s,μ decays: separate Higgs for each generation

The Higgs self-coupling still can have large corrections in viable models. Electroweak baryogenesis requires an increase of a factor ~2.

Add to these, as Jessie Shelton told us, exotic decays to invisible and partially invisible final states, through the Higgs portal.

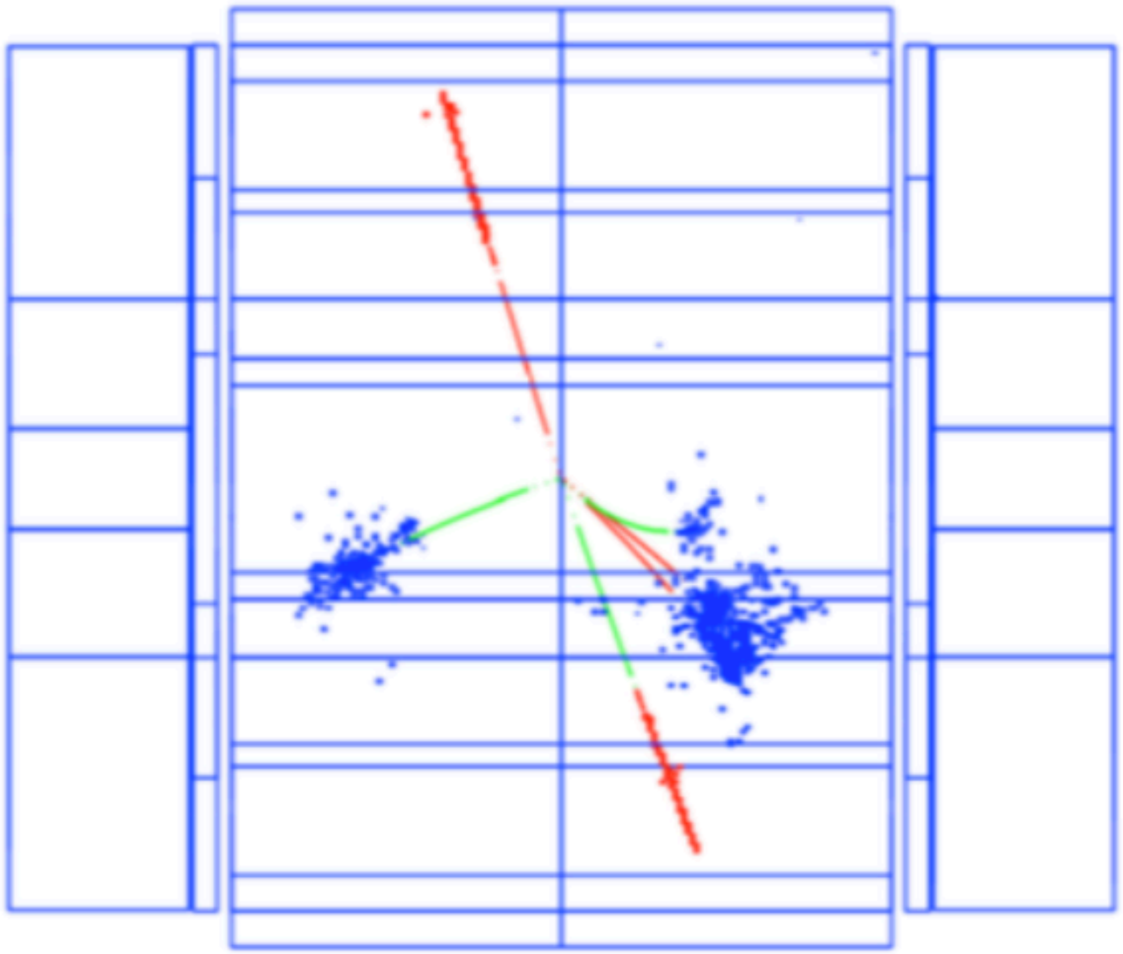
Patrizia Azzi told us that it is possible to reach the relevant level of precision at e+e- colliders in the 240 GeV - 500 GeV energy range.

At LHC, Higgs bosons appear in 1 in 1 billion events.

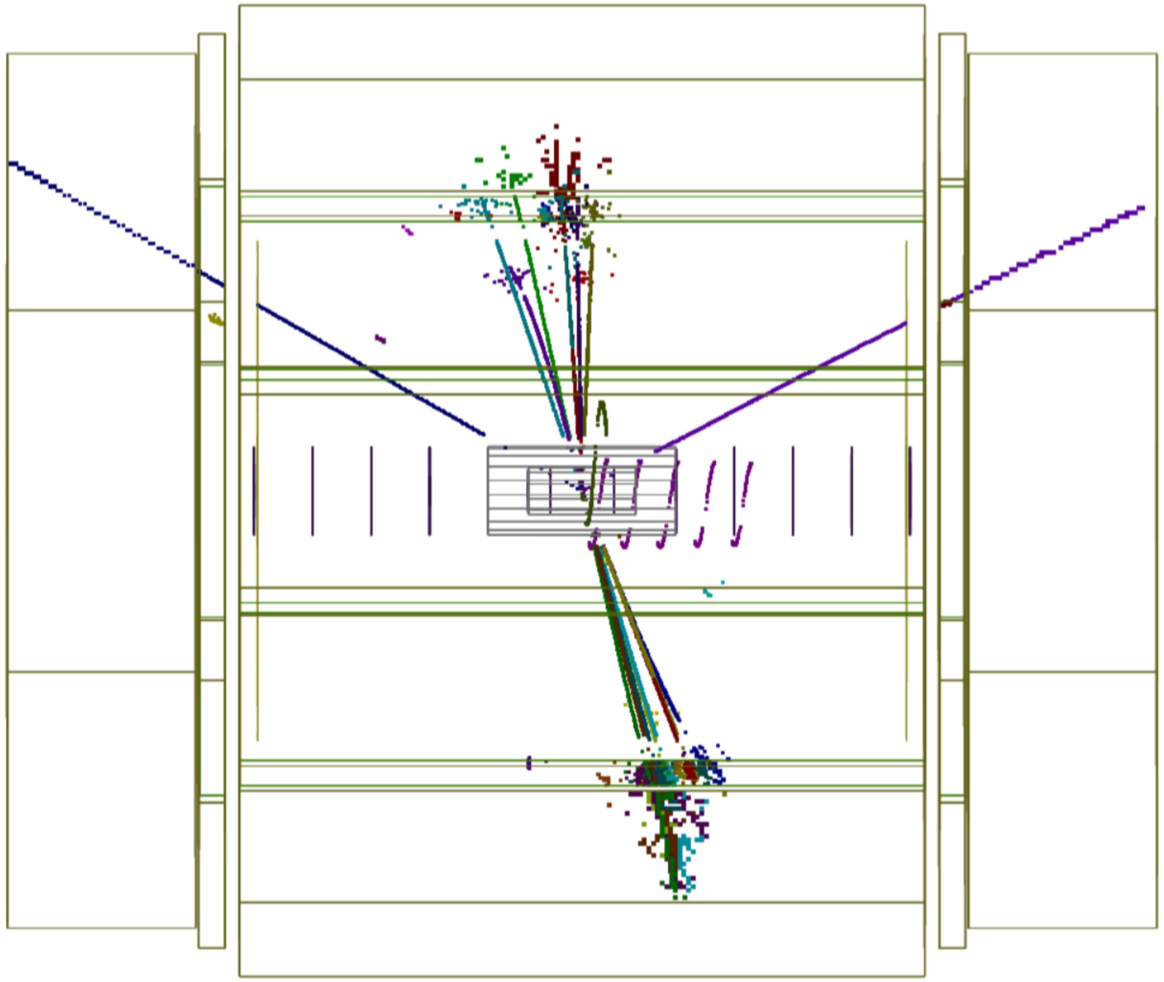
At e+e-, Higgs bosons appear in 1 in 100 events.

So in e+e- we are relatively free from backgrounds, selection effects, and associated biases. We are free to concentrate our efforts on precision.

ILD simulation of $e^+e^- \to Zh\ ,\ Z \to \mu^+\mu^-$



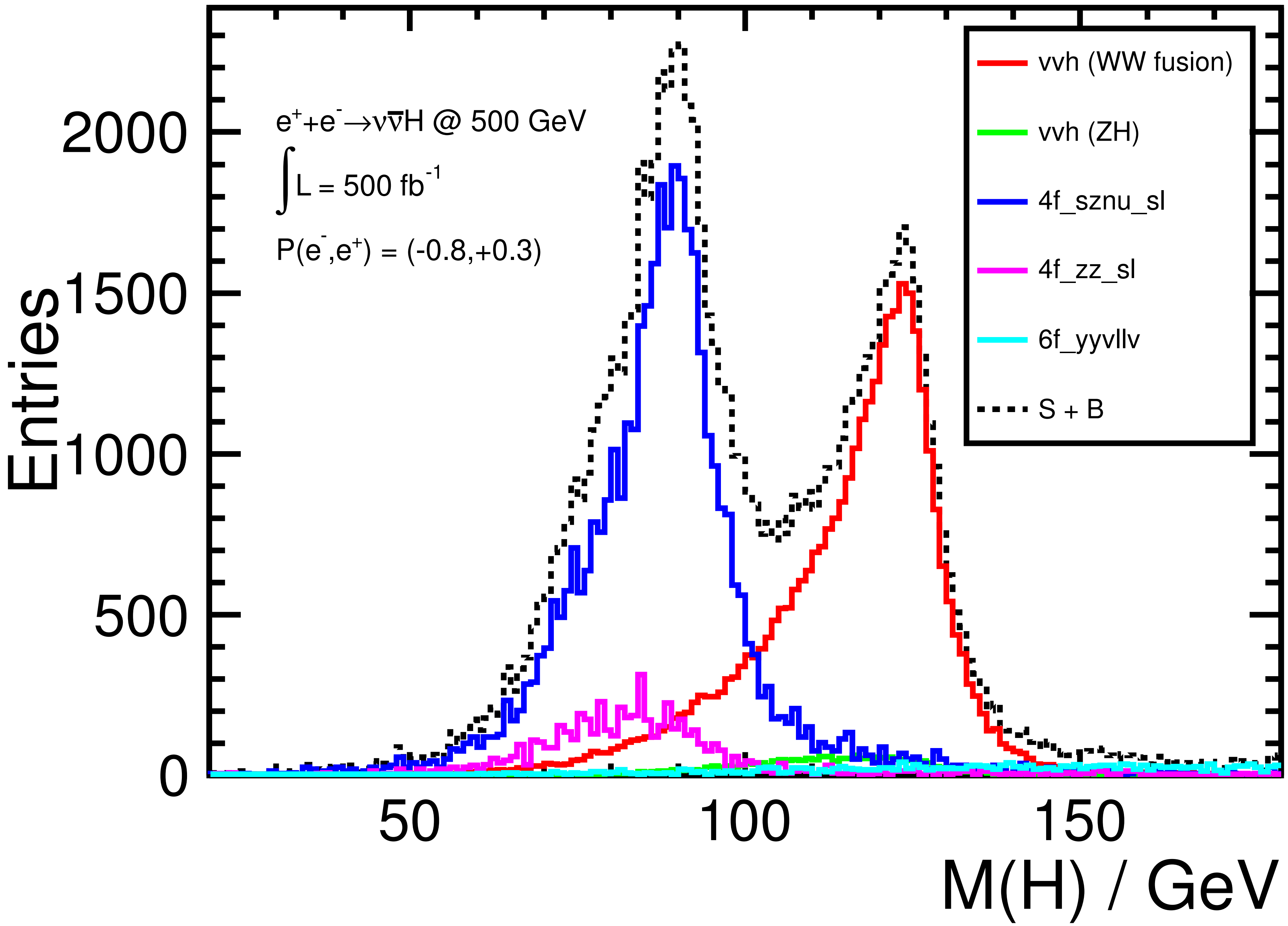
$h \to \tau^+\tau^-$



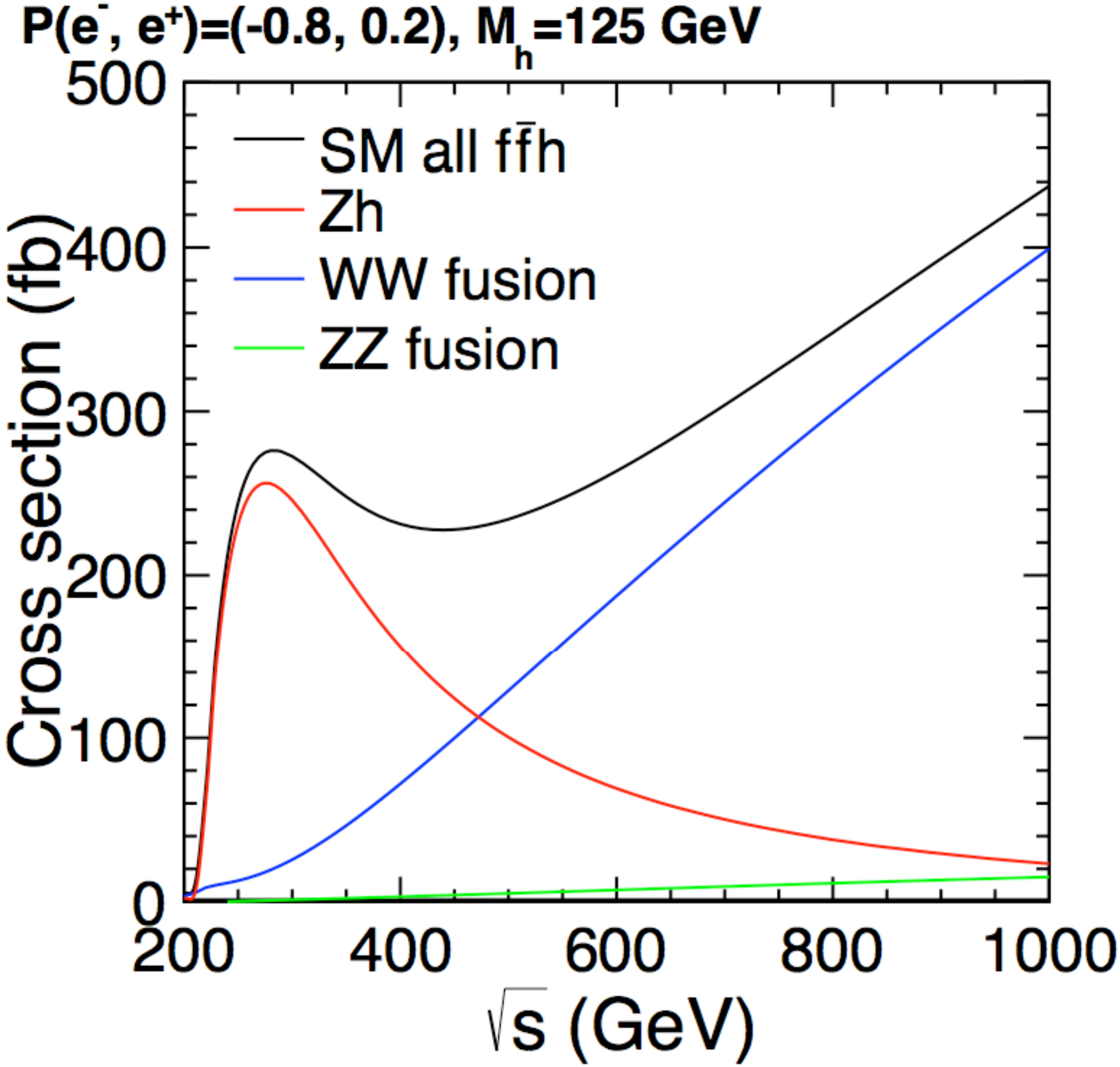
$h \to b\bar{b}$

(thanks to M. Ruan)

$$e^+e^- \rightarrow \nu\bar{\nu} + b\bar{b}$$

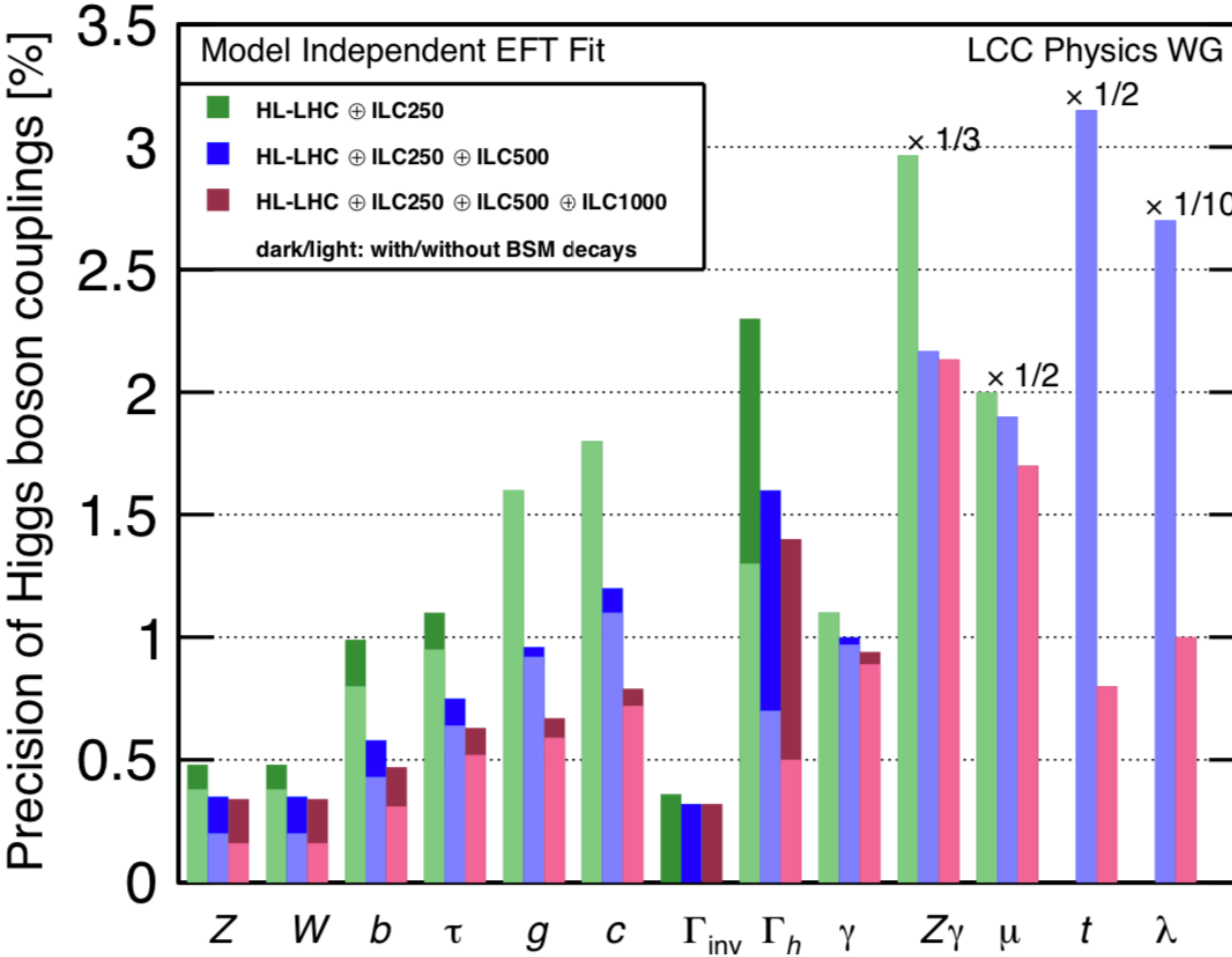


arXiv:1903.01629



P(e-, e+)=(-0.8, 0.2), Mh=125 GeV
Cross section (fb)
500
400
300
200
100
0
200
400
600
800
1000
√s (GeV)
SM all ff̄h
Zh
WW fusion
ZZ fusion

ILC projected precision (all proposals have similar results)



ILC, arXiv:1908.11299

These results require the energy and luminosity, but also detector performance dramatically improved over LHC.

tracking: Higgs mass from recoil to 0.01%

flavor: high efficiency to separate c from b jets

calorimetry: energy measurement x 2 LHC,
making full use of particle flow

hermeticity: down to 10 mrad from the beam direction

For more discussion, see:

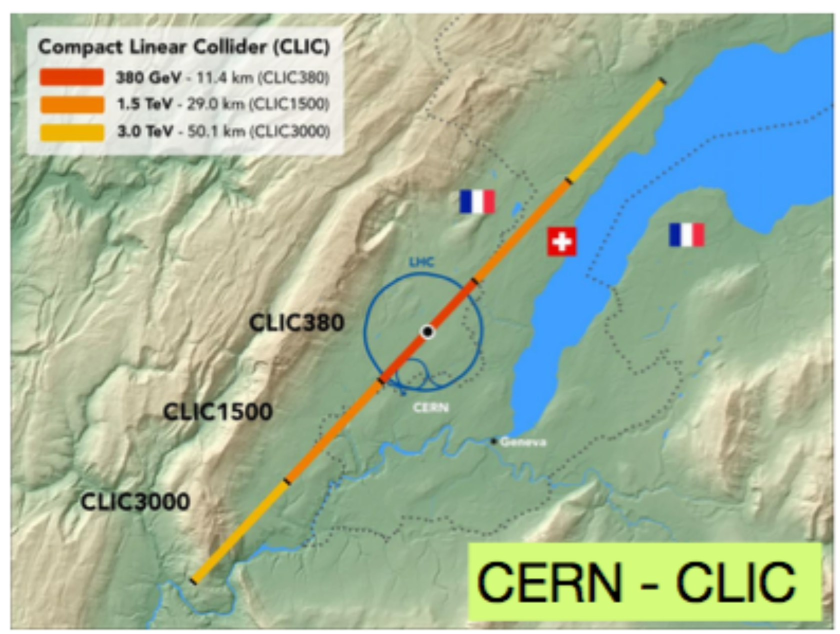
DOE Basic Needs Study on High Energy Physics Detector Development and Research   Dec. 2019

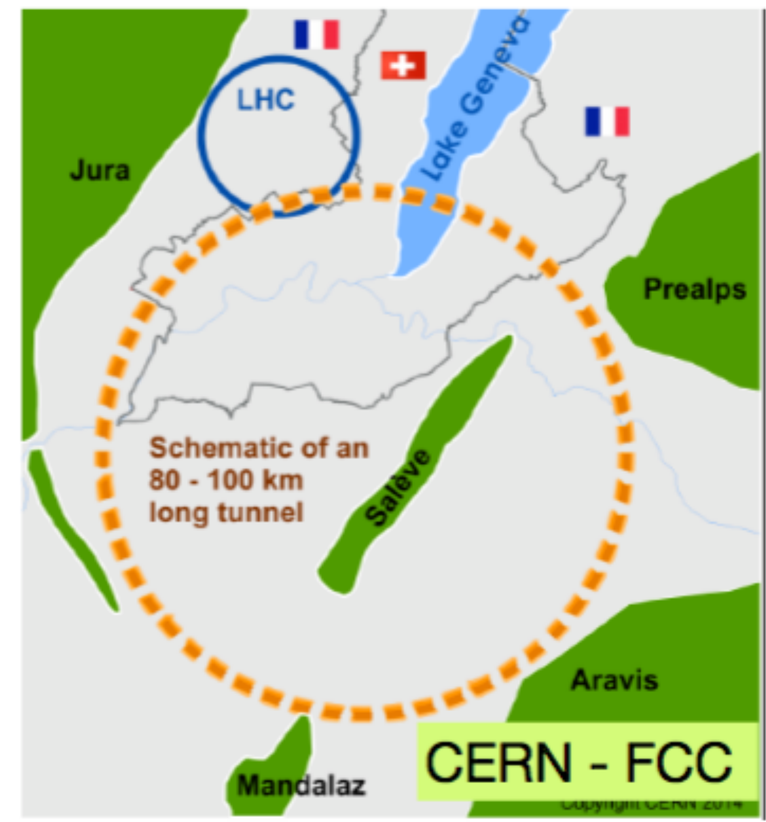
ILC report to the ESS arXiv:1903.01629

You will see from these articles that these goals are achievable.   But actually meeting them in practice will be a challenge that you can engage in.

Azzi described 4 proposed colliders:

FUTURE LEPTONS COLLIDER PROPOSED LOCATIONS





Much effort has gone into debating which approach is the best. The result is that all of these proposals have very similar capabilities, and any one can do the job required.

	HL-LHC	ILC250	ILC500	CLIC380	CLIC1500	CEPC	FCCee240	FCCee350
hZZ	3.6	0.47	0.22	0.66	0.27	0.52	0.47	0.26
hWW	3.2	0.48	0.23	0.65	0.24	0.51	0.46	0.27
hbb	5.1	0.83	0.52	1.0	0.47	0.67	0.70	0.56
hcc	-	1.8	1.2	4.0	1.9	1.9	1.4	1.3
$h\tau\tau$	3.5	0.85	0.60	1.3	0.93	0.70	0.70	0.57
hgg	2.2	1.1	0.79	1.3	0.97	0.79	0.95	0.82
$h\gamma\gamma$	3.7	1.3	1.1	1.4	1.2	1.2	1.2	1.2

ECFA Higgs@Future Colliders arXiv:1905.03764v1

projected uncertainties in Higgs boson couplings, in %
(SMEFT without flavor universality)

For you, there is a much more important question:

Can we get one of the colliders on a time scale relevant to your career ?

In all cases, the technologies are well developed.

But, engineering design and construction may take 15 years. We don't have time to lose.

All of these machines have costs on the order of $10 B. Please ask your supervisors how long it takes to persuade governments to give us the money.

I am sure that many of you are excited by the possibility of accelerators for the 10 TeV mass scale.

I am sorry, but these are very far away, even to be prepared for a technical design and costing.

For FCC-hh, the production of 16T magnets in industry will begin in the 2030’s. Until then, we will not know the cost.

For muon collider, a neutrino beam demonstration facility is needed. This probably will also be in the 2030’s.

Plasma-wakefield electron colliders are probably even further behind.

We could have an e+e- Higgs factory as early as the 2030's. But, the prospects are uncertain. For this to happen, you need to engage with this opportunity now.

The Snowmass 2021 national study of particle physics opportunities is going on now. If you would like to be doing these experiments in 15 years, now is the time to becomes involved. Study the physics case and detector requirements, and ask how you can make a contribution.

In talk, I have discussed the mysteries still associated with the Higgs boson, and tools to solve them.

It is possible that the Standard Model is the last word on particle physics.   But this is not a physicist's conclusion. The Standard Model describes the particle physics data, but it does not explain why.

The alternative is that there is a new layer of fundamental interactions that lies behind the Higgs field. It can explain what is Higgs field is, how it is built, and why it has its properties. These questions must be answered to give a foundation for understanding all other aspects of particle physics.

The precision study of the Higgs boson will give us a new window into these questions. Through this, we can discover the new physics behind the Standard Model and learn about its properties.

This is the opportunity for your generation of particle physicists.

It is time for you to grasp it !