Higgs Studies with e+e- Colliders

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The conveners asked me to discuss:

1. Unique advantages of e+e- for Higgs boson studies
2. How to determine the Higgs boson width
3. Measurement of the Higgs self-coupling in e+e-

1.

The goal of an experimental program on the Higgs boson should be to demonstrate with high significance that the Standard Model is incorrect, and to obtain clues as to what lies beyond it.

To achieve this, we need measurements of Higgs boson couplings that are

precise to or below the 1% level
insensitive to systematic errors
improvable if an anomaly is discovered

This is a difficult mandate to satisfy. It requires high-energy collider experiments designed for high precision.

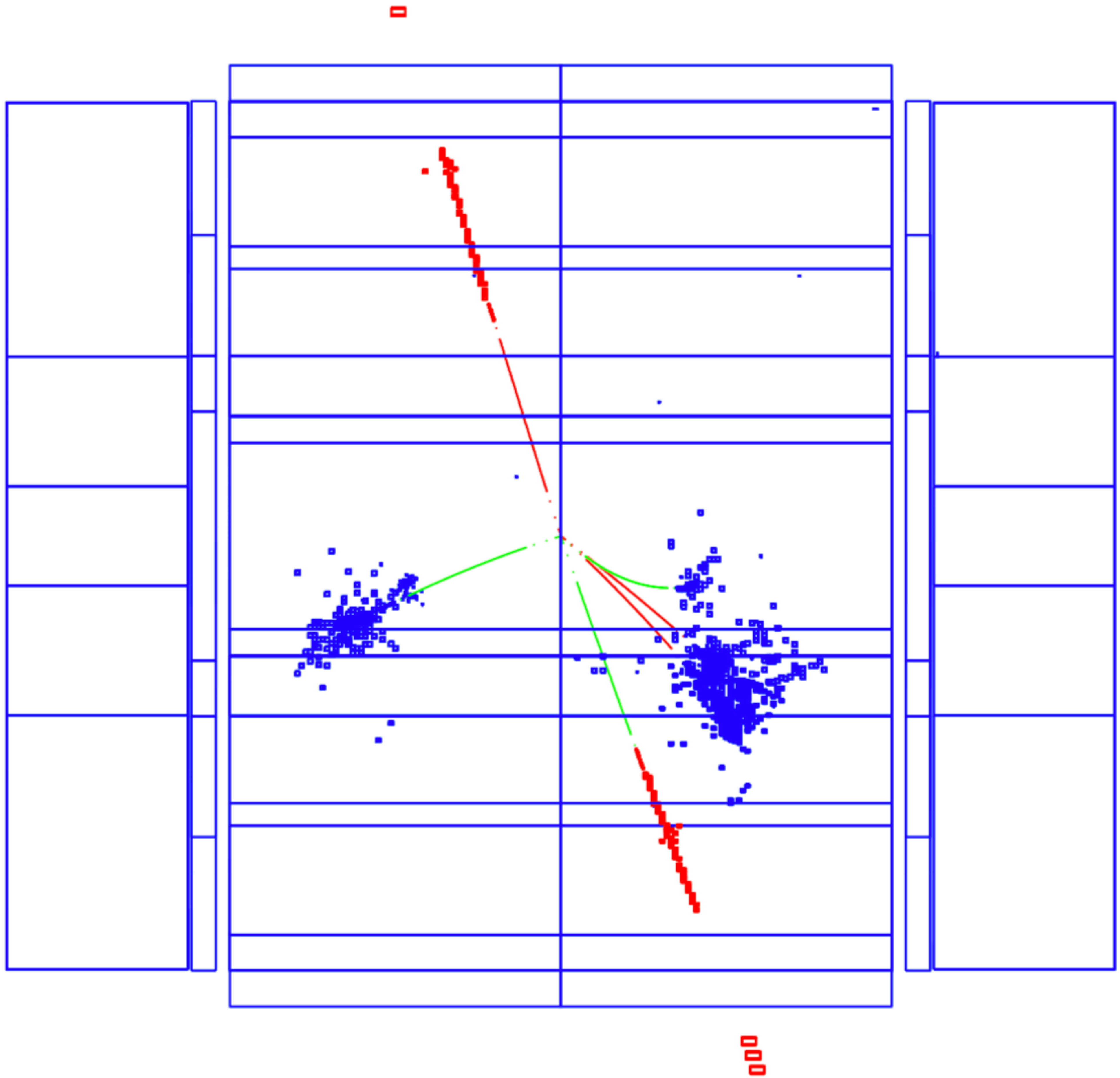
We are convinced that e+e- colliders in general and ILC in particular can satisfy this mandate.

Availability of tagged Higgs boson production (h + Z) at 250 GeV.

Availability of WW fusion production (h + nothing) at higher energies.

“Studying Higgs at the LHC is like doing astronomy in the daytime.” — R. Talman

At linear e+e- colliders, beam polarization also becomes an important tool.



Your goals in the Snowmass study should be

- to understand and independently evaluate this point of view — best, with worked examples

- to imagine how the obvious simplifications of e+e- can make our analyses even more powerful

2.

In the SM, the width Γ_h of the Higgs boson is 4 MeV. Today, there is no practical collider design for which this width is directly measureable with %-level precision

(e.g. at ILC, $\Delta m_h \sim 15 \text{ MeV}$.)

On the other hand, Γ_h is a fundamental quantity for the interpretation of Higgs data. Using $e^+e^- \to Zh$, we can directly measure

$$BR(h \to A\overline{A}) = \frac{\Gamma(h \to A\overline{A})}{\Gamma_h}$$

however, the real quantities of interest are

$$\Gamma(h \to A\overline{A})$$

which are proportional to the squares of Higgs couplings.

To determine Γ_h from data, we need knowledge of all Higgs decays and a model of each decay amplitude. A method that comes as close to this as possible is called "model-independent".

The best idea today for the model is to use the Standard Model Effective Field Theory with the most general set of dimension-6 operators to represent the most general BSM corrections to SM Higgs decays.

I gave a pedagogical description of this method in

arXiv:2003.05435

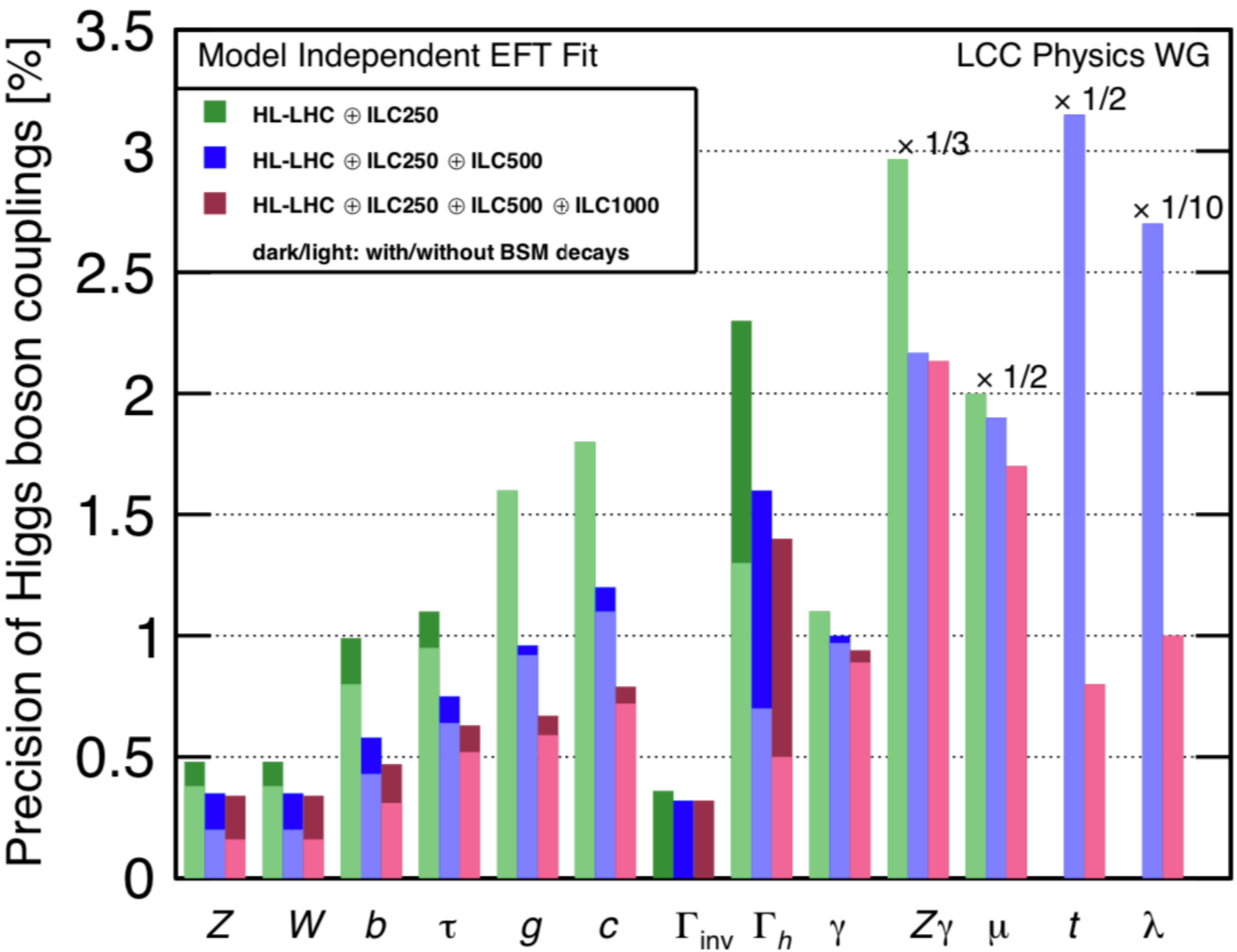
There are a large number of SMEFT operators, but, for the analysis of e+e- data, 18 operator coefficients suffice. We can find enough observables to determine these uniquely.

One should think through how to treat exotic Higgs boson decays in this framework.

The procedure of the ILC group has been to include 2 additional parameters: a BR for invisible decays and a BR for decays not-in-any-category. There are exceptions, but in most models this is compatible with a SMEFT description of the SM decays.

The relation between full BSM models and SMEFT parameters is intricate and needs clarification at Snowmass.

In particular, the mapping from SMEFT parameters to model ("the Higgs inverse problem") is not well understood and needs study,



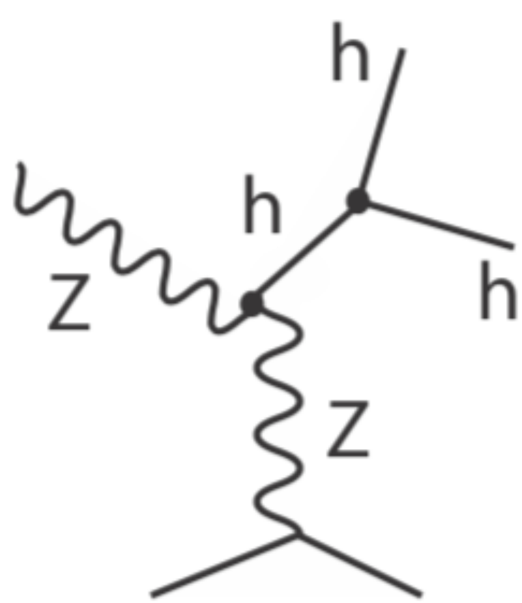
for more details and tables, see arXiv:1908.11299 and arXiv:1903.01629 (Section 11)

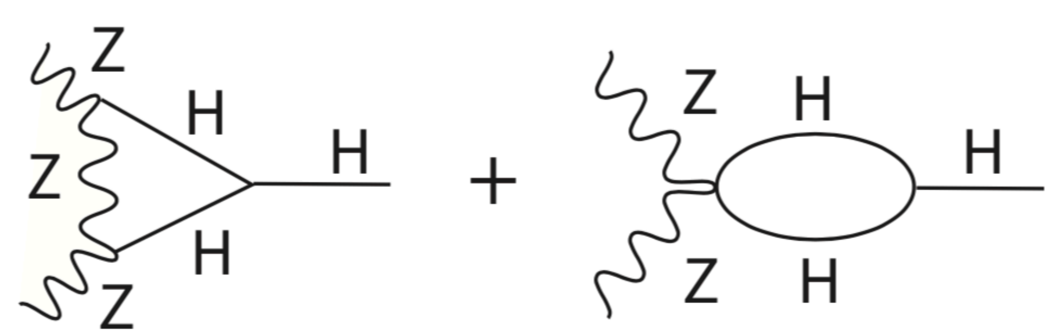
3.

An important goal of a future Higgs program is the measurement of the Higgs self-coupling.

There are two methods to determine the Higgs self-coupling at e+e- collider: (see arXiv:1910.00012 , Chapter 9)

- measure hh production, and interpret in a model
- measure h production reactions to the % level and look for the small effect of Higgs loops





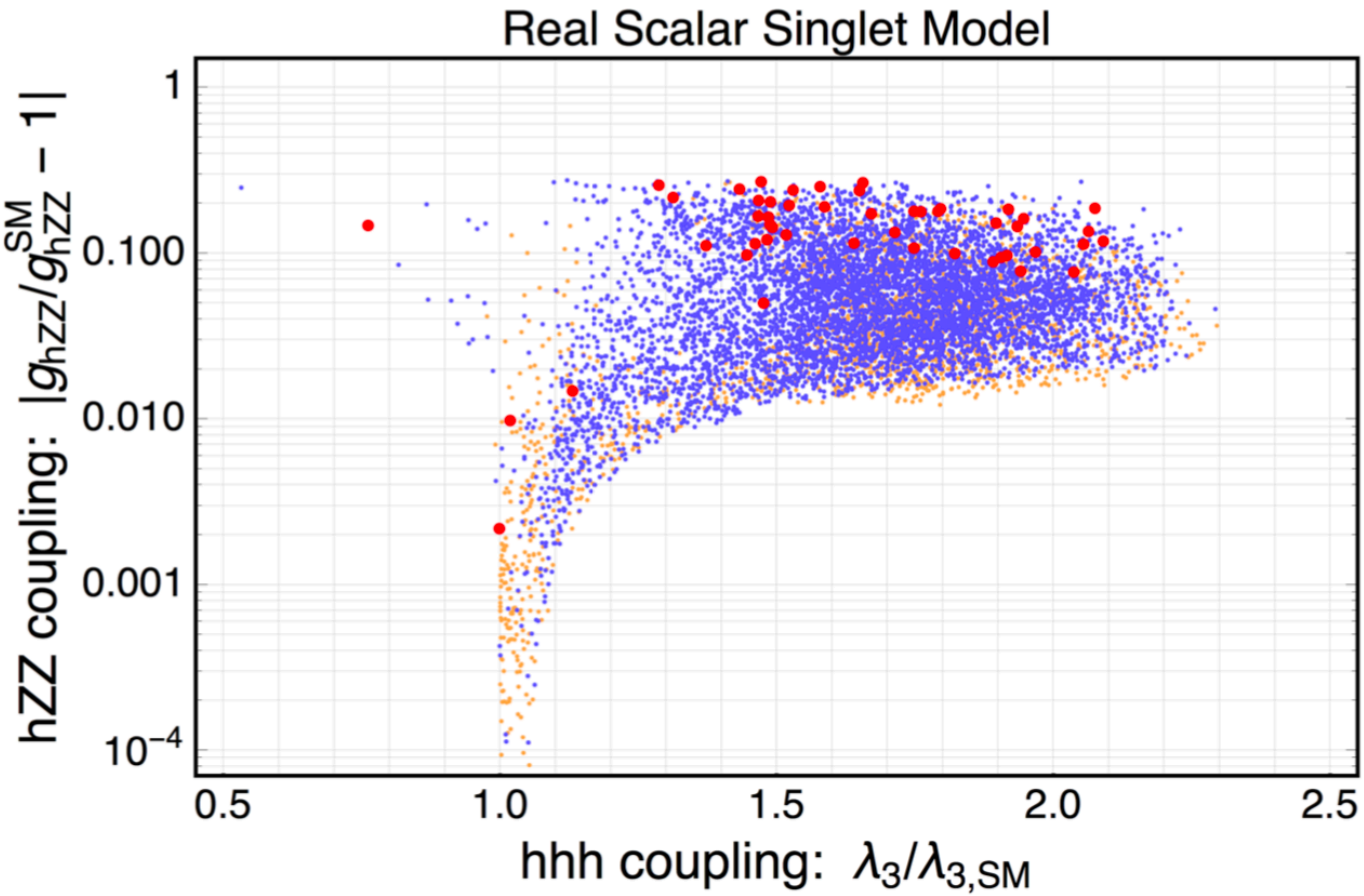
The discovery and measurement of the processes

$$e^+e^- \to Zhh \qquad\qquad e^+e^- \to \nu\bar{\nu}hh$$

has been studied by the ILC and CLIC groups. The first is accessible only at 500 GeV and the second at still higher energy.

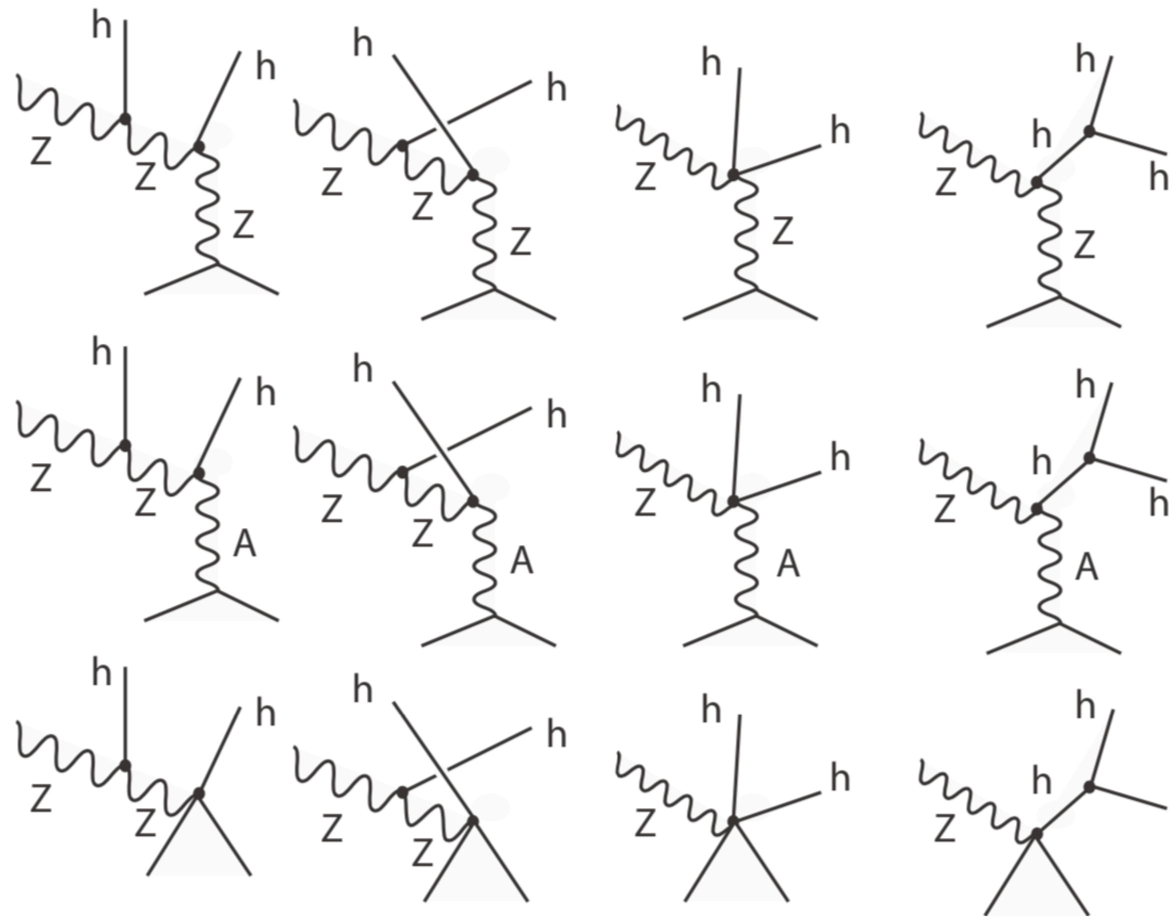
A very complete reference on the Zhh reaction is the DESY Ph.D. thesis of Claude Durig (available on INSPIRE). Signal/background discrimination is challenging, and we believe there is significant room for improvement.

It is important not to consider the Higgs self-coupling in isolation, since BSM models that affect this also typically affect other Higgs couplings



Huang, Long, and Wang

For $e^+e^- \to Zhh$, modelling BSM physics with SMEFT,

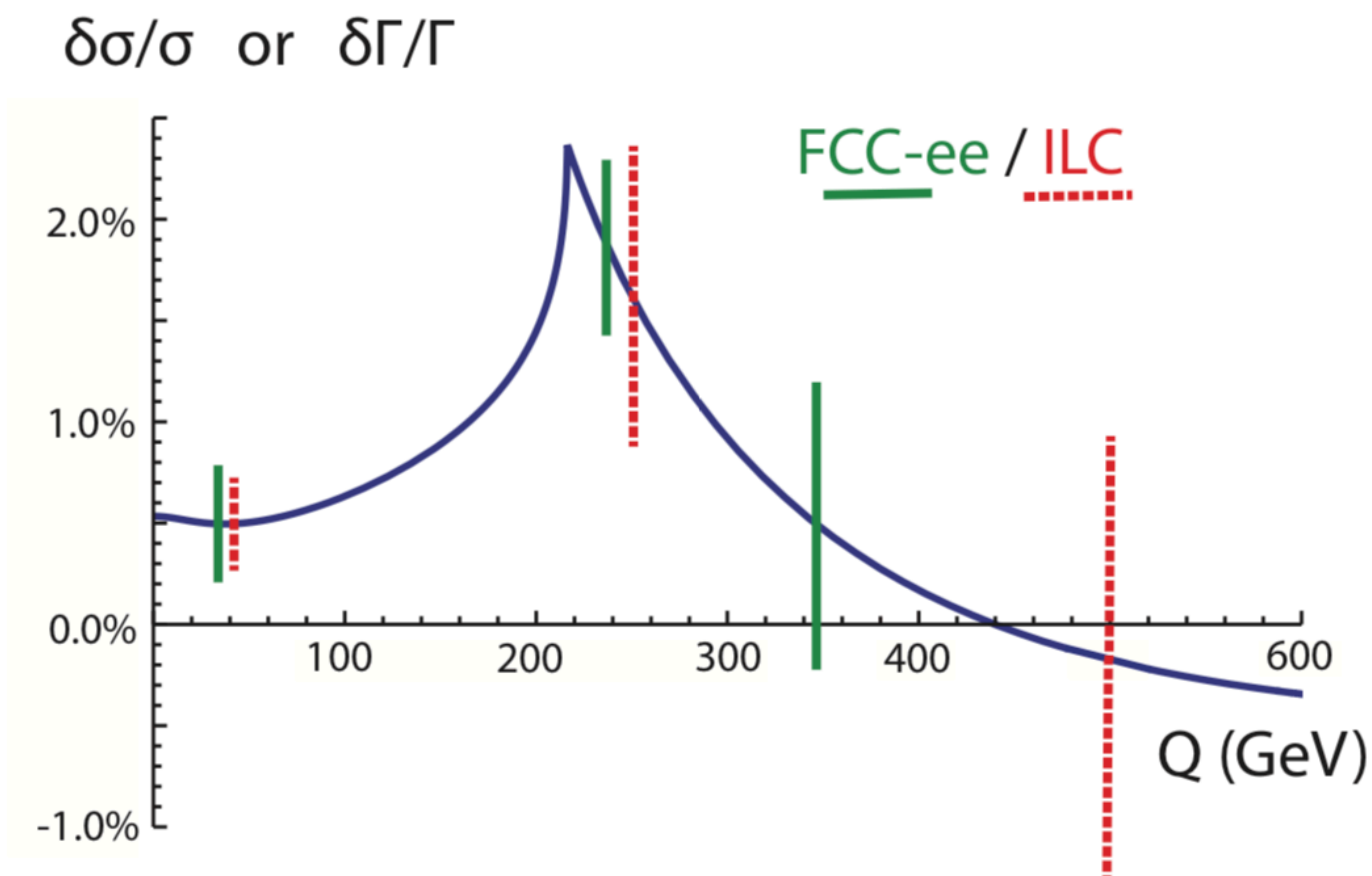


Barklow et al. find

$$\sigma/\sigma^{SM}(ZHH) = 1 + 0.56c_6 - 4.15c_H + 15.1(c_{WW}) + 62.1(c_{HL} + c'_{HL}) - 53.5c_{HE} + \cdots ,$$

However, at ILC, the additional coefficients will be constrained very strongly, and their effect is at most 2.5%.

In the single-h method, we are look for a radiative correction of size 1.5%. However, McCullough argued that this can be extracted (in principle), since it has a characteristic dependence on momentum.



The effect on the $e^+e^- \to Zh$ cross section at 250 GeV is

$$\sigma/\sigma^{SM}(ZH) = 1 + 0.015 c_6 - c_H + 4.7(c_{WW}) + 13.9(c_{HL} + c'_{HL}) - 12.1 c_{HE} + \cdots .$$

A summary, from ECFA Higgs report, is

collider	single-H	HH direct	combined
HL-LHC	100-200%	50%	50%
CEPC_{240}	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
CLIC_{380}	50%	–	50%
CLIC_{1500}	49%	36%	29%
CLIC_{3000}	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
FCC-hh	-	5%	5%

single-h values are combined with HL-LHC

All of these analyses would benefit from more eyes and better understanding.