Model-Independent Determination of the Higgs Self-Coupling

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One of the important goals of the study of the Higgs boson is to determine experimentally the shape of the Higgs potential.

In the Standard Model at leading order, the Higgs potential has the form

$$V = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

After symmetry breaking,

$$V = \frac{1}{2} m_h^2 h^2 + \lambda_3 h^3 + \cdots$$

where

$$\lambda_3 = m_h^2 / 2v$$

In more general models, though, the value of λ_3 can be very different, and can reflect the physics by which the Higgs potential was created.

It is thus important to measure λ_3 as accurately as possible.

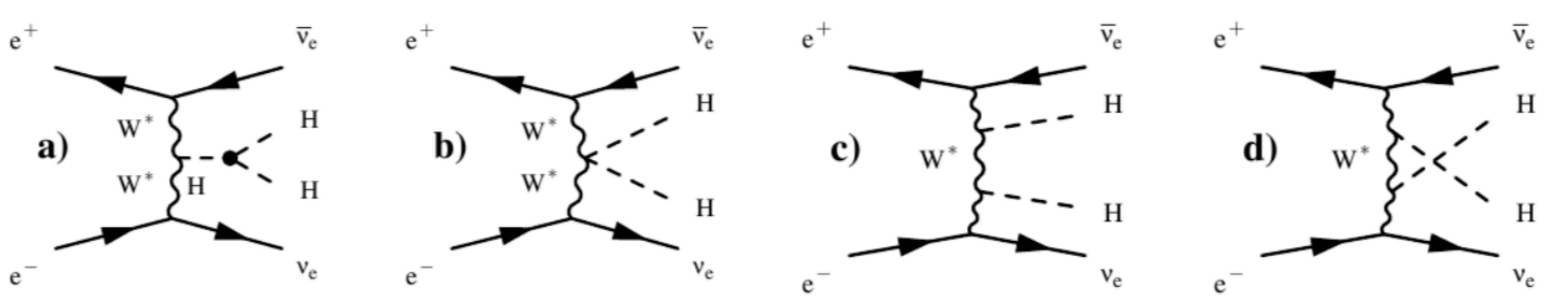
Though for most Higgs couplings we expect only small deviations from the SM expectation, λ_3 can be an exception.

In particular, in models of electroweak baryogenesis, where the electroweak phase transition must be first-order, λ_3 can differ by a factor of 2 from its SM value.

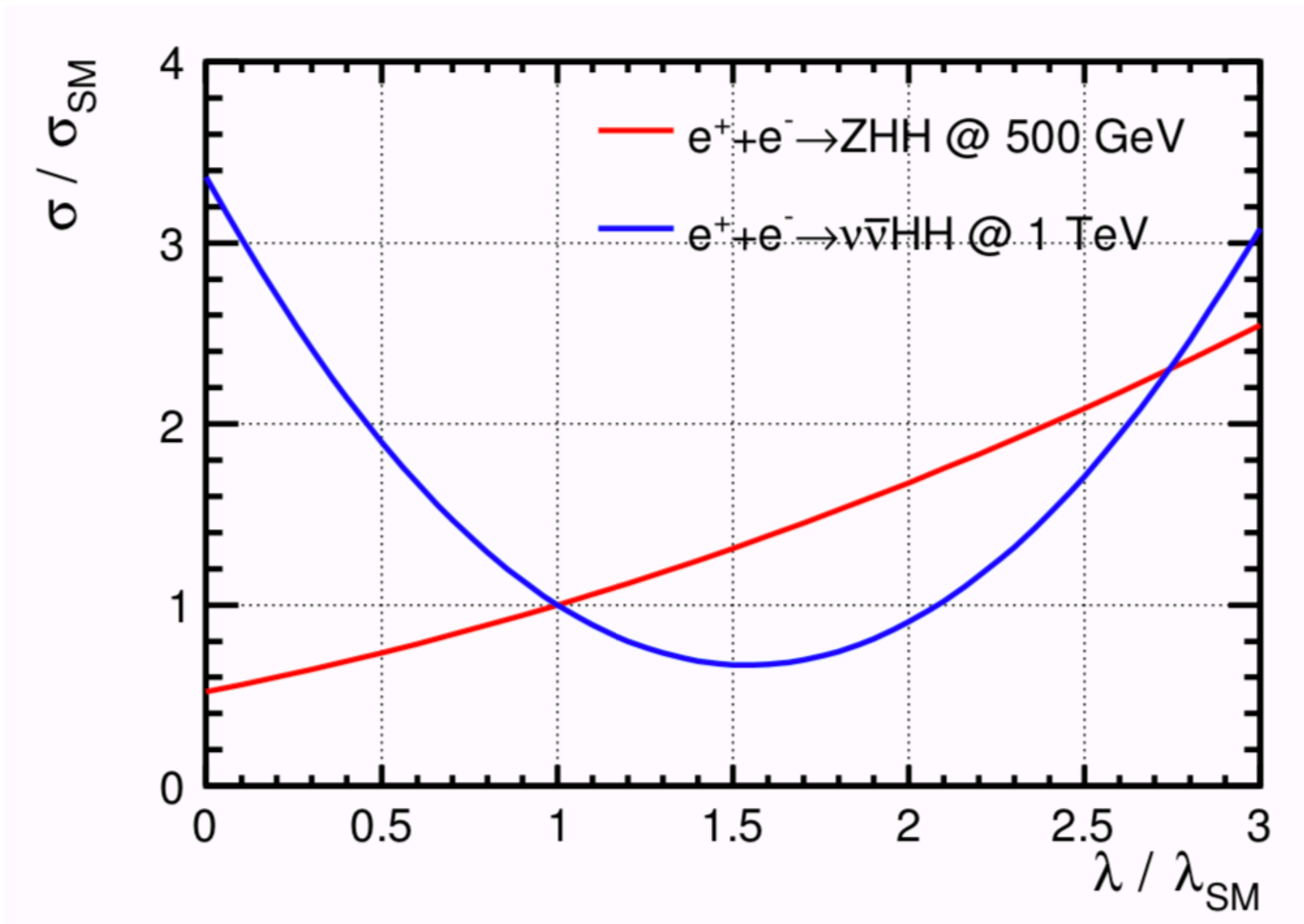
In principle, it is straightforward to measure λ_3 by measuring the cross section for double Higgs production processes. At e+e- colliders, these are the processes

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

In both cases, the triple Higgs vertex appears in interference with larger contributions from the more usual SM vertices. For example,

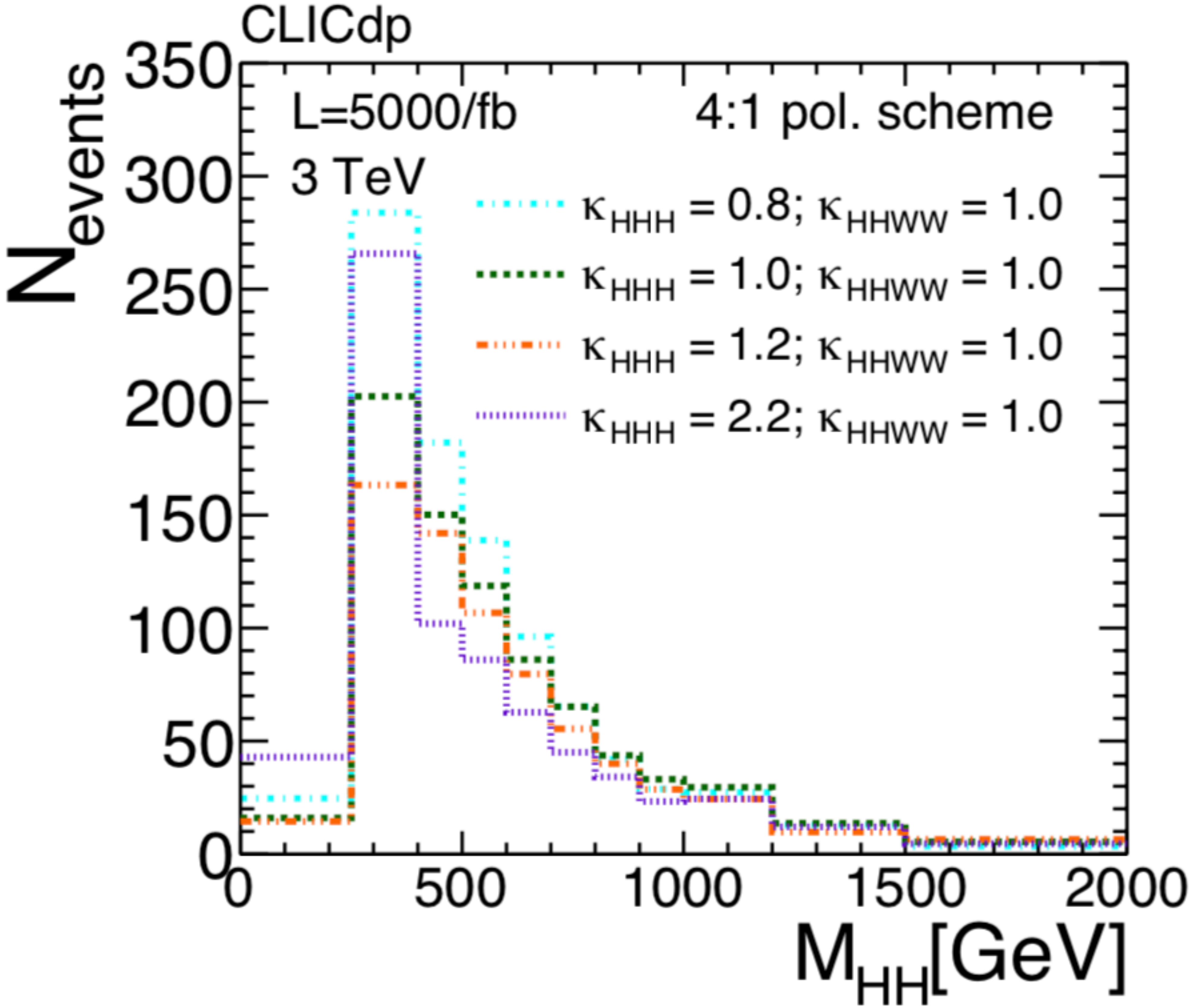


It is interesting that the two e+e- processes have opposite signs of the interference.   Thus, measuring both cross sections gives enhanced sensitivity in either case.



In the case of the WW fusion process, where there is destructive interference, the measurements of the cross section for $\lambda_3/SM > 1$ give two solutions.

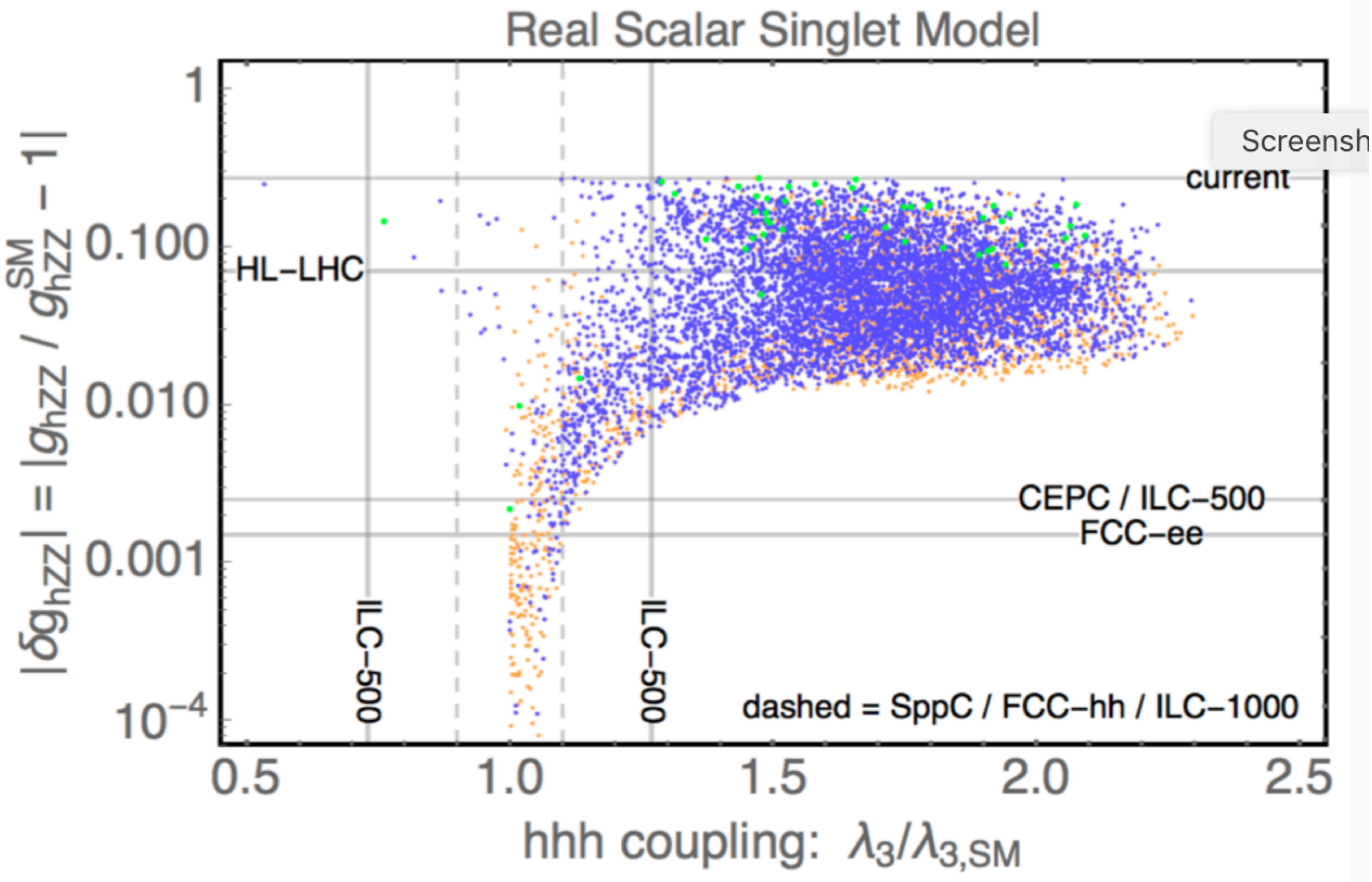
This degeneracy is broken by measuring the spectrum of $m(HH)$. This point is emphasized in the CLIC studies for 3 TeV.



CLICdp
L=5000/fb
3 TeV
4:1 pol. scheme
κ_{HHH} = 0.8; κ_{HHWW} = 1.0
κ_{HHH} = 1.0; κ_{HHWW} = 1.0
κ_{HHH} = 1.2; κ_{HHWW} = 1.0
κ_{HHH} = 2.2; κ_{HHWW} = 1.0
N_{events}
M_{HH}[GeV]
0
50
100
150
200
250
300
350
500
1000
1500
2000

There is another difficulty in interpreting these analyses. The SM diagrams - including the λ_3 diagrams - depend on many vertices other than the vertex. If these vertices are altered by the same BSM models that produce a deviation in λ_3 , we need to take those effects into account.

Can we specifically ascribe a change in the hh production cross section to λ_3 ?

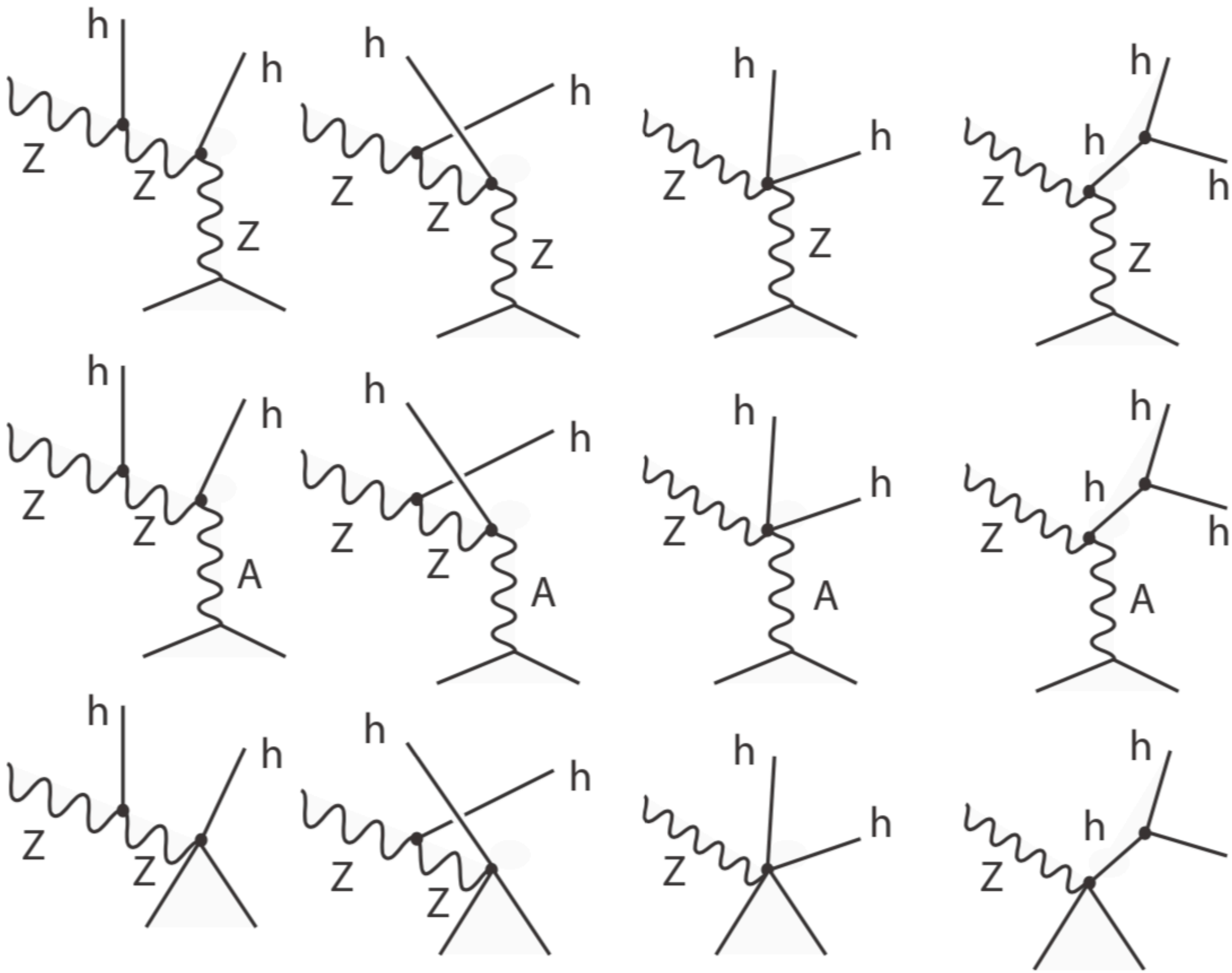


example of Higgs-singlet mixing models, from Huang, Long, and Wang, arXiv:1608.06619

A method of analyzing this is to recompute the cross section in the SMEFT with dimension-6 operators treated in leading order.   16 additional operators contribute.

$$\Delta\mathscr{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 + \frac{c_{WW}}{2v^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu}$$
$$+ i\frac{c_{HL}}{v^2}J^\mu_H(\bar{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}J^{a\mu}_H(\bar{L}\gamma_\mu t^a L) + i\frac{c_{HE}}{v^2}J^\mu_H(\bar{e}\gamma_\mu e)\,,$$

$$J^\mu_H = \Phi^\dagger \overleftrightarrow{D}^\mu \Phi \qquad J^{a\mu}_H = \Phi^\dagger \overleftrightarrow{D}^\mu t^a \Phi$$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In Barklow et al arXiv:1708.09097, we computed $\sigma(e^+e^- \to Zhh)$ in this framework. For the case of unpolarized beams, the result is

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

Some of these coefficients are very large. Fortunately, the constraints from precision electroweak and the expected constraints from Higgs factories can control these parameters. For the ILC 500 program

A	$[< A^2 >]^{1/2}$	A	$[< A^2 >]^{1/2}$
c_H	0.65	$(c_{HL} + c'_{HL})$	0.014
$(8c_{WW})$	0.039	c_{HE}	0.009
$(-4.15c_H + 15.1(8c_{WW}))$	2.8	$62.1(c_{HL} + c'_{HL}) - 53.5c_{HE}$	0.85

It is important to carry out a similar analysis for

$$\sigma(e^+e^- \to \nu\overline{\nu}hh)$$

I apologize; this is still in progress.

There is another method to determine λ_3 that makes use of single-Higgs reactions. At one loop, contributes a radiative correction to hAA vertices. If we can identify this effect using very high precision Higgs measurements, we can use it to measure λ_3 .

This effect was emphasized by McCullough. But the title of his paper was

“An Indirect Model-Dependent Probe of the Higgs Self-Coupling” (arXiv:1312.3322)

More recently, Di Vita et al (arXiv:1711.03978) demonstrated that this method can be made model-independent in the context of a full SMEFT-based Higgs fit.

An improved analysis is contained in the recent Higgs@Future Colliders working group report (deBlas etal.,arXiv:1905.03764).

This method has been emphasized by the FCC-ee group, noting that FCC-ee cannot reach energies where hh production can be studied.

Detecting this effect within the SMEFT context is very challenging.

On a previous slide, I showed the equation for SMEFT effects on $\sigma(e^+e^- \to Zhh)$. The analogous relation for $\sigma(e^+e^- \to Zh)$ is

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

I would now like to explain how this can be done.

To introduce this, I should make two points:

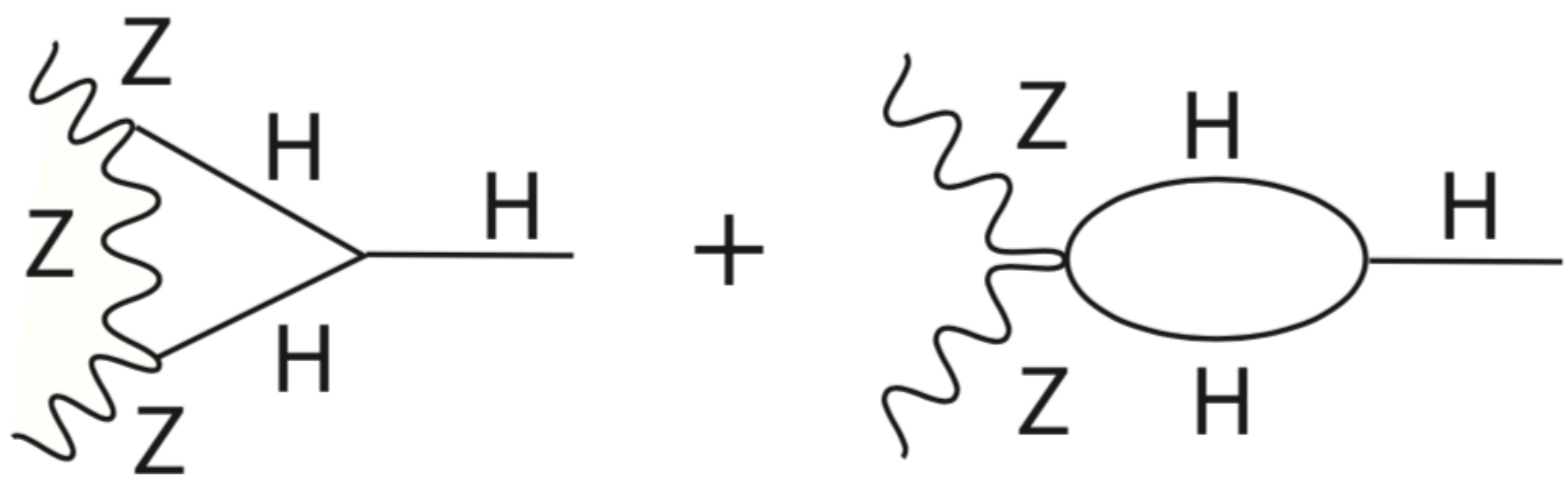
1. An argument is needed if we are to include the radiative correction from c_6 while ignoring radiative corrections from other dimension-6 coefficients. A possible justification is that there are models in which c_6 is required to be of order 1 while other dimension-6 coefficients are of order 1%.

   Jung et al used a similar argument to single out the radiative correction due to top quark operators. The argument is (to me) less persuasive in that case.

2. There are radiative corrections from c_6 to all hAA vertices. However, if these corrections are Q^2-independent, they are degenerate with SMEFT coefficients that also correct these vertices. For example, the Q^2-independent part of the correction to the hbb vertex would be degenerate with the SMEFT coefficient $c_{\Phi b}$ which contributes at tree level.

Further, if we measure a given vertex only at one value of Q^2, the effect of Q^2 on that vertex cannot be distinguished. In the e+e- single-Higgs program, actually, this is true for all Higgs vertices except for the hWW and hZZ vertices.

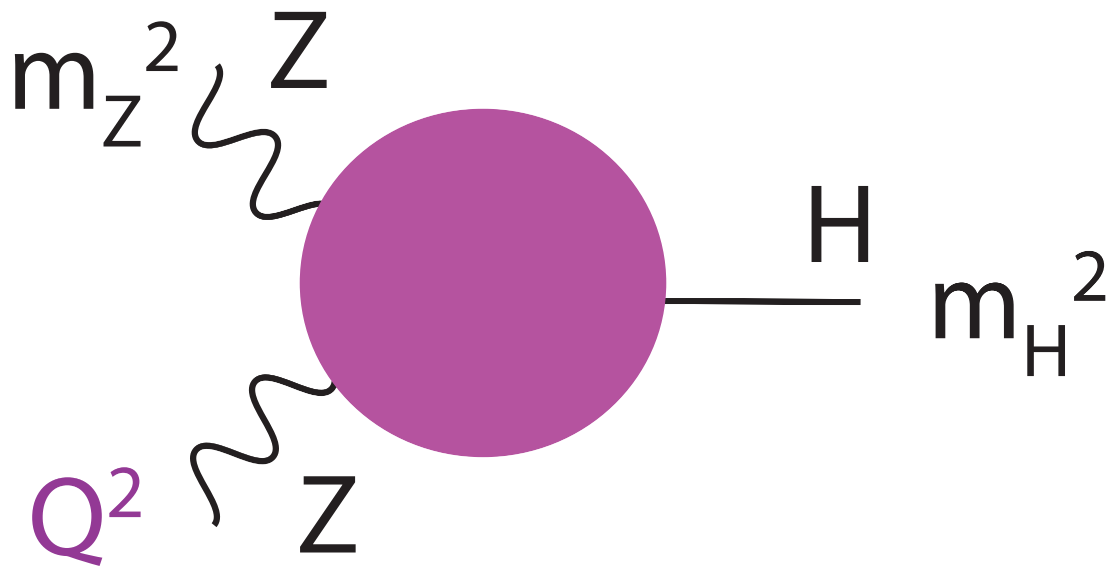
So, we have to concentrate on the c_6 effect on those particular vertices. These come from the diagrams



and the similar diagrams for W.

These diagrams are to be computed in Unitarity gauge. In a general R_ξ gauge, there is one more diagram, with Π^0or Π^+ in the loop . The sum of these 3 diagrams is ξ -independent.

McCullough's paper provided the insight needed to observe the Q^2 -dependent effect. We need to study



This vertex is available at

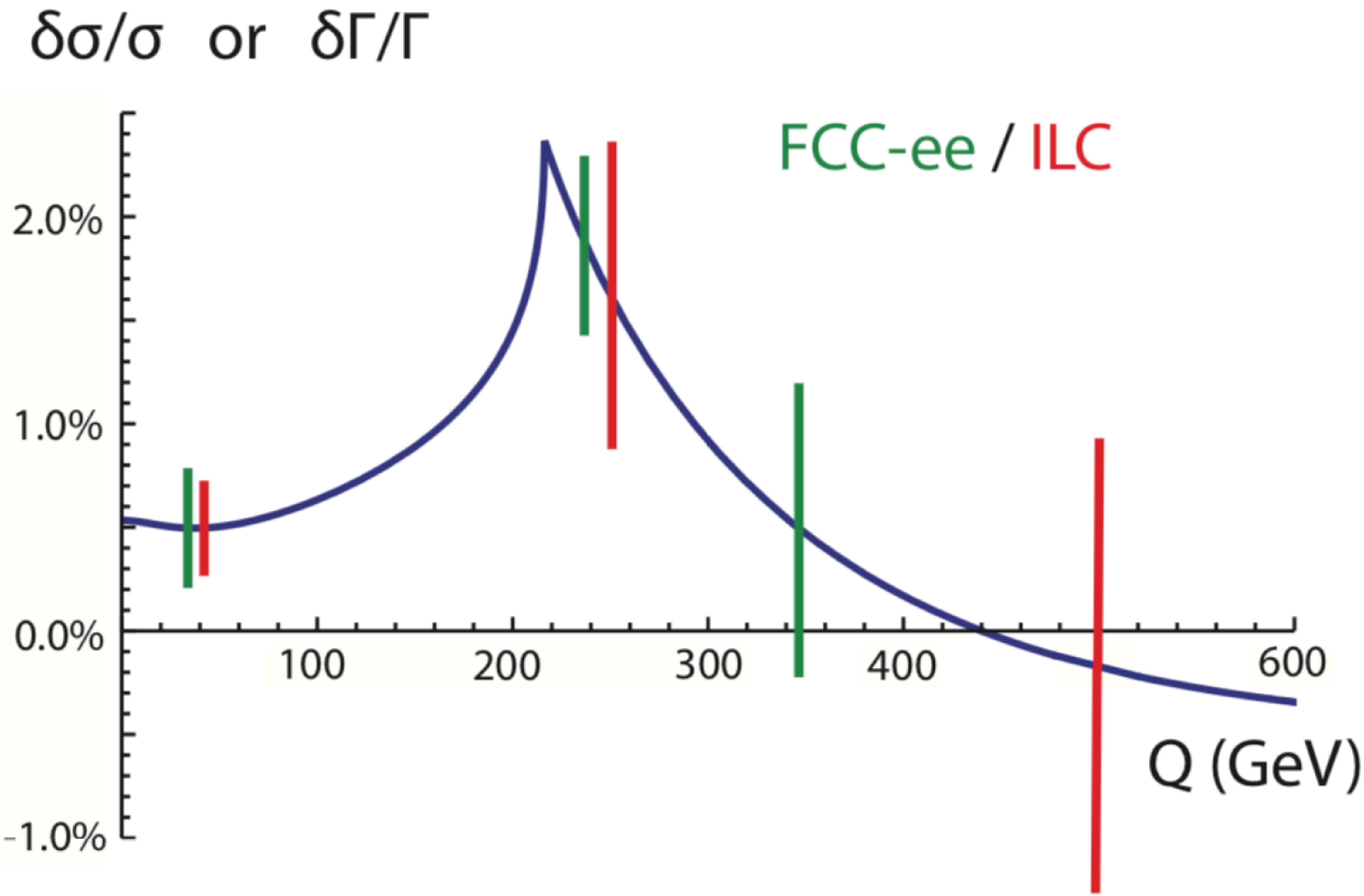
$$Q^2 = E_{CM^2} \text{ in } e^+e^- \to Zh$$

$$Q^2 = (40)^2 \text{ in } h \to ZZ$$

$$Q^2 = (30)^2 \text{ in } h \to WW$$

$$Q^2 \lesssim 0 \text{ in } e^+e^- \to \nu\overline{\nu}h$$

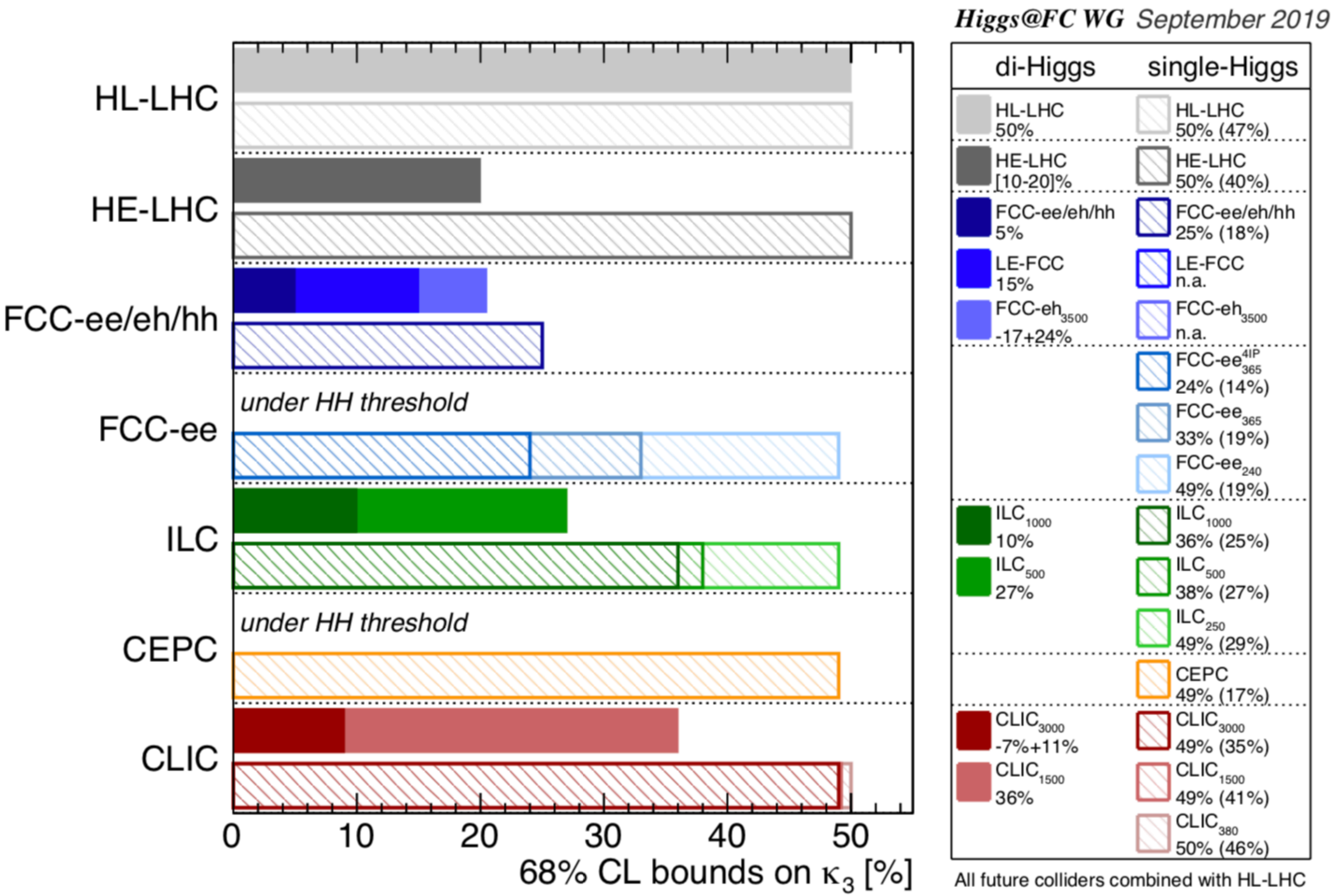
Its functional form as a funtion of Q^2 is quite remarkable.



δσ/σ or δΓ/Γ
FCC-ee / ILC
2.0%
1.0%
0.0%
-1.0%
100
200
300
400
600
Q (GeV)

Results of fits by the H@FC working group. I extract an assumed 50% uncertainty constraint from HL-LHC.

collider	1-parameter	full SMEFT
CEPC 240	18%	-
FCC-ee 240	21%	-
FCC-ee 240/365	21%	44%
FCC-ee (4IP)	15%	27%
ILC 250	36%	-
ILC 250/500	32%	58%
ILC 250/500/1000	29%	52%
CLIC 380	117%	-
CLIC 380/1500	72%	-
CLIC 380/1500/3000	49%	-


Higgs@FC WG September 2019
HL-LHC
HE-LHC
FCC-ee/eh/hh
FCC-ee
ILC
CEPC
CLIC
under HH threshold
under HH threshold
0
10
20
30
40
50
68% CL bounds on κ_3 [%]
di-Higgs
single-Higgs
HL-LHC 50%
HL-LHC 50% (47%)
HE-LHC [10-20]%
HE-LHC 50% (40%)
FCC-ee/eh/hh 5%
FCC-ee/eh/hh 25% (18%)
LE-FCC 15%
LE-FCC n.a.
FCC-eh$_{3500}$ -17+24%
FCC-eh$_{3500}$ n.a.
FCC-ee$^{4IP}_{365}$ 24% (14%)
FCC-ee$_{365}$ 33% (19%)
FCC-ee$_{240}$ 49% (19%)
ILC$_{1000}$ 10%
ILC$_{1000}$ 36% (25%)
ILC$_{500}$ 27%
ILC$_{500}$ 38% (27%)
ILC$_{250}$ 49% (29%)
CEPC 49% (17%)
CLIC$_{3000}$ -7%+11%
CLIC$_{3000}$ 49% (35%)
CLIC$_{1500}$ 36%
CLIC$_{1500}$ 49% (41%)
CLIC$_{380}$ 50% (46%)
All future colliders combined with HL-LHC

Notice that measurement of $\sigma(e^+e^- \to Zh)$ at two different energies is needed to allow the SMEFT fit to converge.

This is not available at ILC 250 only.

Between ILC 500 and FCC-ee 365, the former has a longer moment arm but the latter has higher statistics in the cross section measurement.

For CLIC, the second energy stage is at 1500 GeV. At this energy, $\sigma(e^+e^- \to Zh)$ is already too small to give a competitive result.

Junping Tian and I are redoing these fits using the Barklow et al. framework.

At this moment, we are using the coefficients of c_6 from the Di Vita et al. paper in the formulae for total cross sections or rates. There is a small effect from angular distributions; this is not yet included.

In our analysis, c_6 is defined to be the coefficient in the hWW and hZZ diagrams only. Terms in these diagrams proportional to $(Q^2)^0$ and $(Q^2)^1$ are degenerate with shifts in c_H and c_{WW}.

ILC 250 2 ab-1

	c_6	c_H	c_b	$8c_{WW}$	c_{HL}	a_{other}
c_6 only	27					
c_6, c_H	199	2.8				
Higgs-fermion	467	7.0	1.9			
WW couplings	482	7.2	2.0	0.096		
precision EW	489	7.3	2.0	0.26	0.041	
exotic decays	489	7.3	2.0	0.26	0.041	0.95
H@FC c_6	36					
H@FC full SMEFT	X					

ILC 2 ab-1 at 250 4 ab-1 at 500

	c_6	c_H	c_b	$8c_{WW}$	c_{HL}	a_{other}
c_6 only	25					
c_6, c_H	41	0.40				
Higgs-fermion	44	0.48	0.50			
WW couplings	44	0.50	0.51	0.049		
precision EW	56	0.62	0.53	0.13	0.014	
exotic decays	58	0.99	0.53	0.13	0.014	0.77
H@FC c_6	36					
H@FC full SMEFT	58					

FCC-ee 5 ab-1 at 240 , 1.5 ab-1 at 365

	c_6	c_H	c_b	$8c_{WW}$	c_{HL}	a_{other}
c_6 only	18					
c_6, c_H	50	0.63				
Higgs-fermion	54	0.72	0.52			
WW couplings	54	0.75	0.53	0.035		
precision EW	56	1.1	0.53	0.19	0.0074	
exotic decays	57	1.1	0.56	0.19	0.0074 0.56	
H@FC c_6	21					
H@FC full SMEFT	44					

FCC-ee 4 detectors: 12 ab-1 at 240 , 4 ab-1 at 365

	c_6	c_H	c_b	$8c_{WW}$	c_{HL}	a_{other}
c_6 only	12					
c_6, c_H	29	0.34				
Higgs-fermion	32	0.40	0.33			
WW couplings	32	0.42	0.34	0.032		
precision EW	35	0.57	0.34	0.12	0.0063	
exotic decays	35	0.61	0.35	0.12	0.014	0.063
H@FC c_6	15					
H@FC full SMEFT	27					

It would be very interesting to understand the source of the differences between the H@FC analysis and ours.

We are pursuing this with Christophe Grojean and Jorge de Blas.

It has become clear that it is possible to extract values of the Higgs self-coupling from e+e- measurments in a way that is model-independent (within the class of models described by SMEFT).

Our current analysis have almost converged. More improvements are in progress.

We expect model-independent measurements to the precision

ILC 500	h observables	60%
FCCee	h observables	40-60%
ILC 500	hh production	27%
ILC 1000 or CLIC	hh production	10%