EFT Fits for Triple Higgs Couplings at Lepton Colliders

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2018. 07. 06 @ ICHEP 2018

1708.08912, 1708.09079 with
T. Barklow, K. Fujii, J. List, T. Ogawa, M. Peskin, J. Tian

Takehome messages

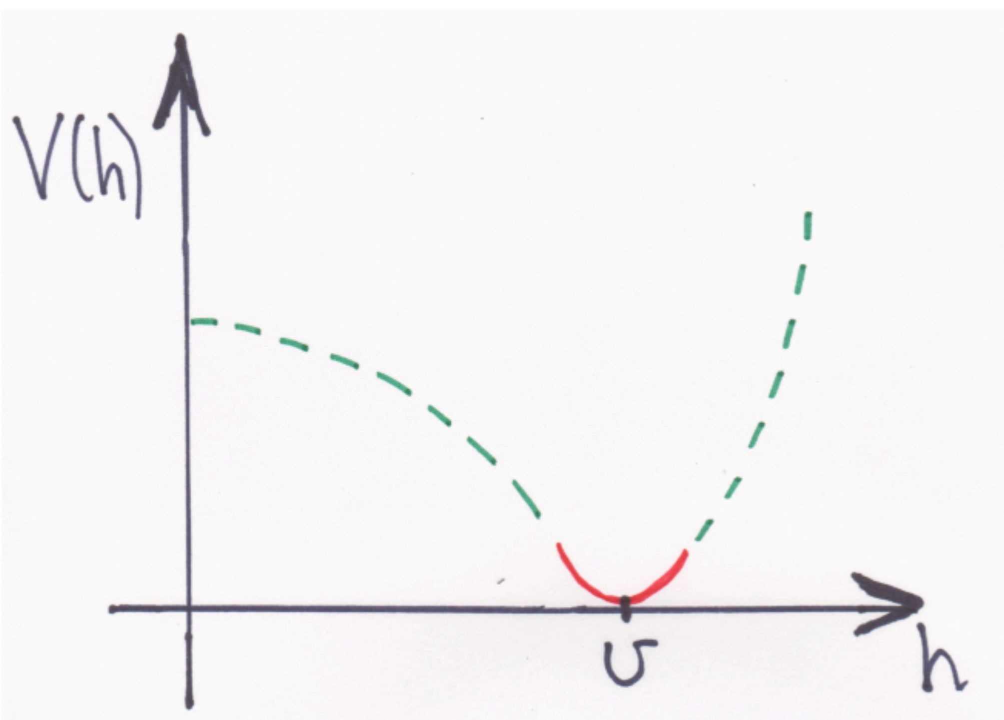
To measure Higgs potential “deviations”:

1. A general approach considering all Non-SM contributions together is needed.
(NB: deviation means non-SM contributions, we don’t know a priori)

2. Best LEP EWPT observables also needs to be updated.

3. Usual kappa or mu analysis cannot be used.

Higgs potential



by M.Perelstein

- What we know now:

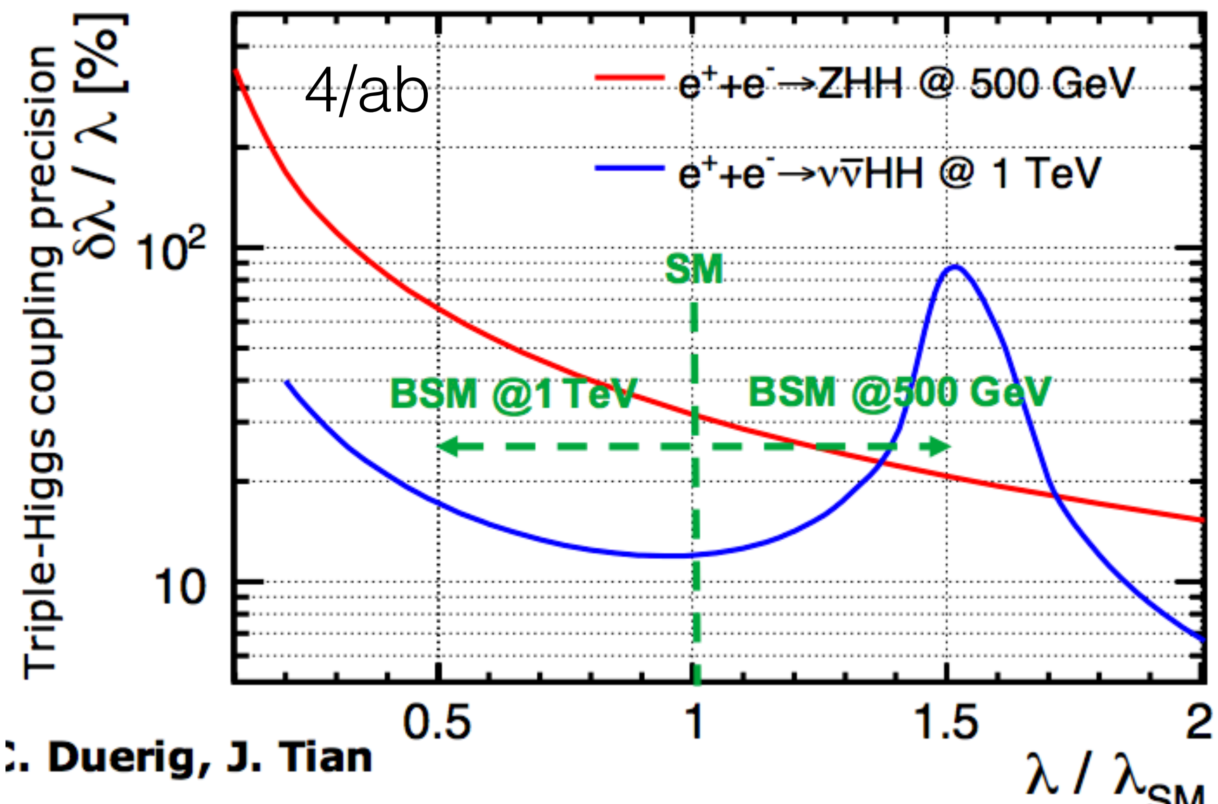
$$V'(h) = 0 \ @ \ h = v \approx 250 \text{ GeV}$$

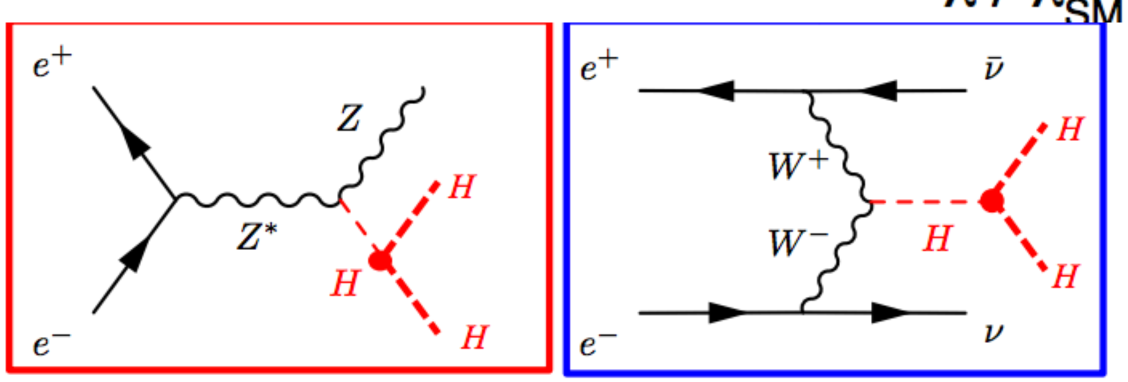
$$m_h^2 = V''(v), \ m_h \approx 125 \text{ GeV}$$

- Measuring Higgs cubic coupling is the next step in extending our knowledge of the shape of V:

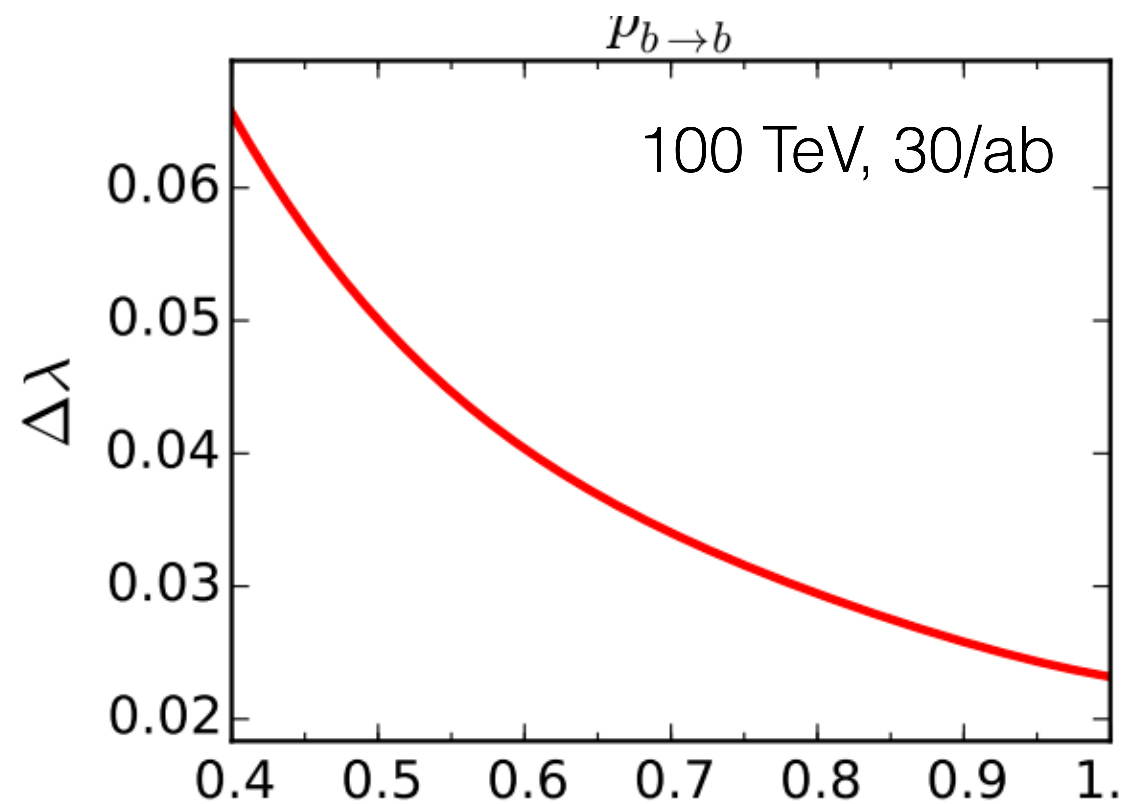
$$\lambda_3 = \frac{1}{6} V'''(v)$$

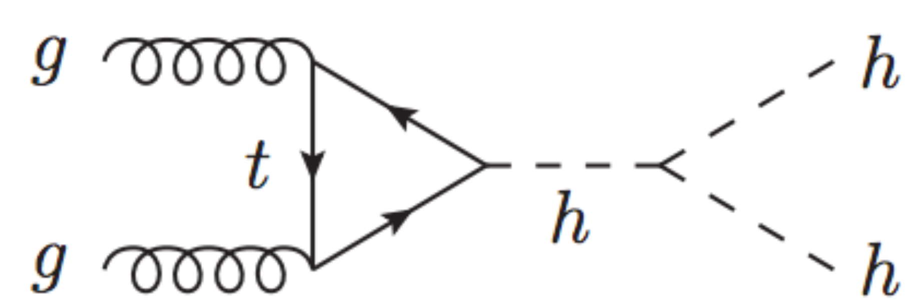
How we usually think about triple Higgs measurement





Diagrams with triple-Higgs coupling





Extracting triple Higgs

- These results of Delta lambda might be good enough if the only question is to test the SM.
- If there's a deviation, there's a new physics! Not only lambda, but many others will be non-SM.
- To interpret Higgs-potential deviation from the SM, it is needed to separate deviations in the Higgs triple coupling from possible deviations of other SM parameters.

Kappa analysis not enough

- Often, a single kappa is used for Higgs coupling ratio w.r.t the SM value.

- For WW and ZZ, in particular, it is not enough.

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$

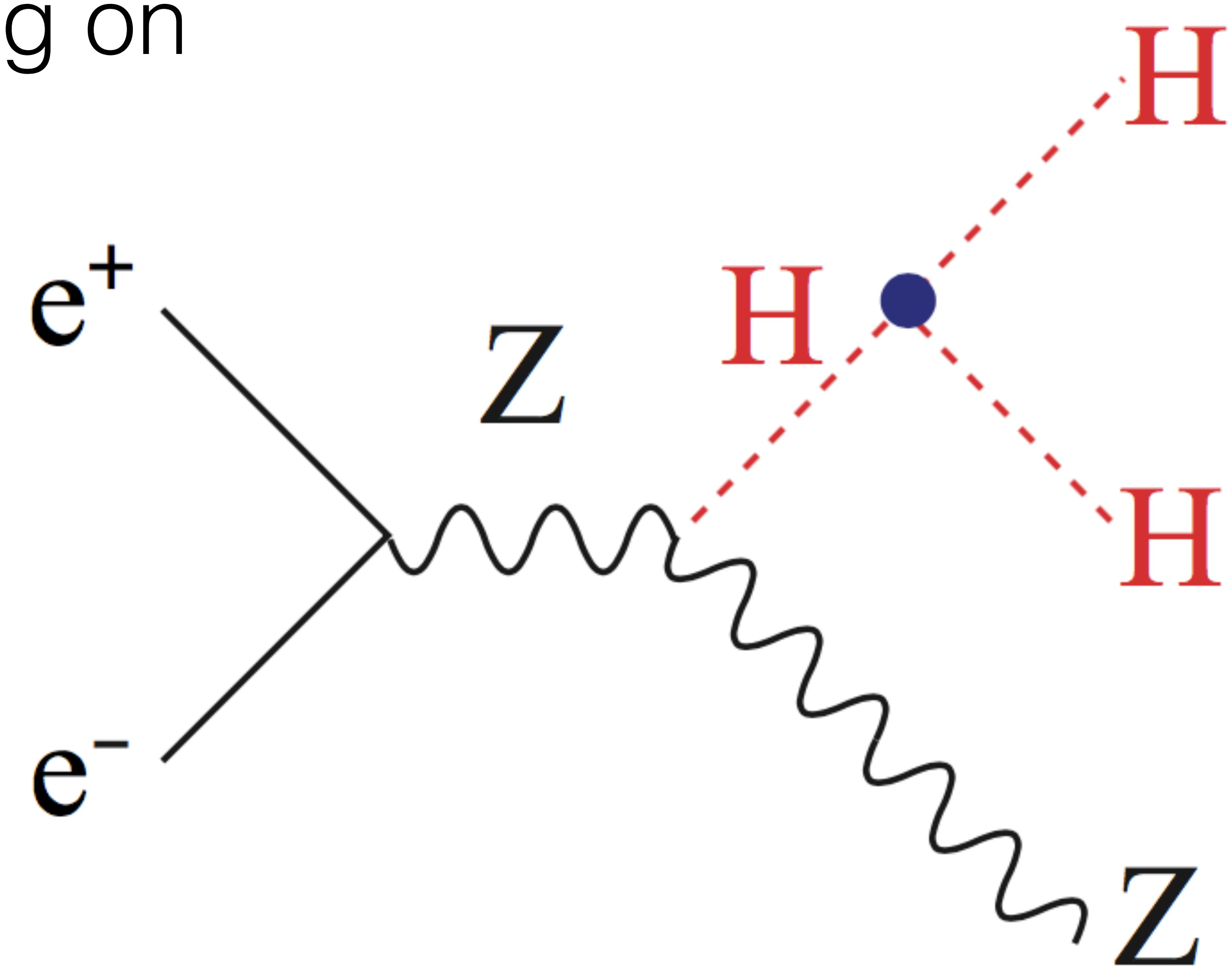
$$\sigma(e^+e^- \to Zh) = (SM)\cdot(1 + 2\eta_Z + (5.7)\zeta_Z)$$

$$\Gamma(h \to ZZ^*) = (SM)\cdot(1 + 2\eta_Z - (0.50)\zeta_Z)$$

- Contribute differently to production and decays, and are also not constants (energy-dependent).

How shall we do?

Focusing on



HEFT as a model-independent framework

- In the HEFT,
  the deviation of the Higgs potential (triple Higgs coupling in particular) is associated with

$$\Delta\mathcal{L} = -\frac{c_6\lambda}{v^2}|\Phi^\dagger\Phi|^3$$

HEFT as a model-independent framework

- In the HEFT,
  the deviation of the Higgs potential (triple Higgs coupling in particular) is associated with

$$\Delta \mathcal{L} = -\frac{c_6 \lambda}{v^2} |\Phi^\dagger \Phi|^3$$

- However,,,
  many other SM and EFT parameters contribute to the same double Higgs observables.

10 d=6 operators

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

These 10 HEFT ops consist of:
(1) at least one Higgs or EW gauge,
(2) only Higgs, EW gauge and electrons

All 10 ops contribute!

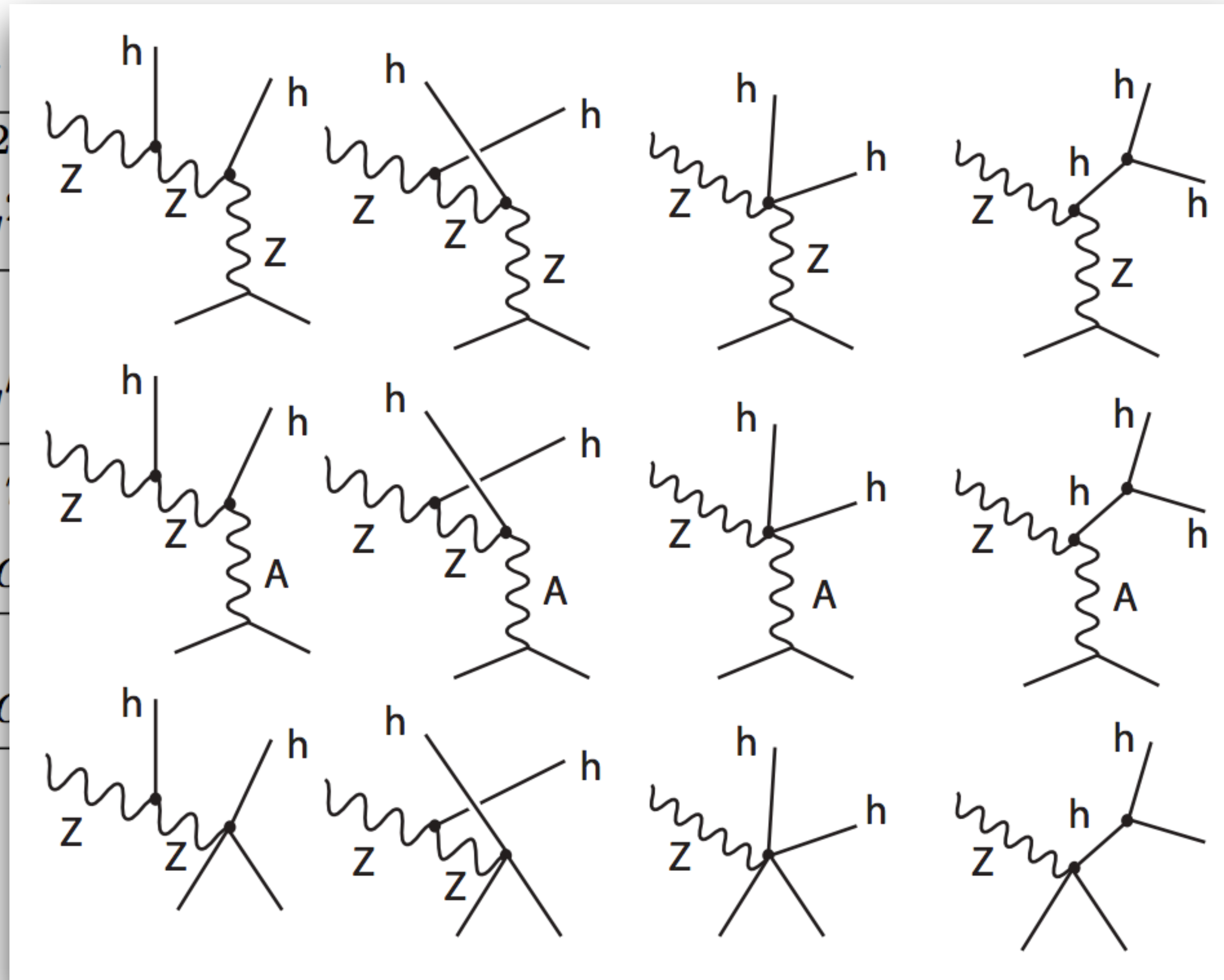
$\Delta\mathcal{L} = \frac{c_H}{2v^2}$ … $\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$

$+\frac{g}{}$ …

$+\frac{g}{}$ …

$+i$ … $\gamma_\mu t^a L)$

$+i$ …



(1) at least one Higgs or EW gauge,
(2) only Higgs, EW gauge and electrons

First of all, c6 is our main parameter for triple Higgs coupling

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \boxed{\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3}$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

But both c6 and cH shape triple Higgs (and Higgs potential) Zhh alone cannot distinguish them.

$$
\begin{aligned}
\Delta\mathcal{L} = & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu} \\
& + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
& + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L) \\
& + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e)\ .
\end{aligned}
$$

But cH renormalizes the Higgs field.
Thus, single Higgs measurements can be relevant.

$$\Delta\mathcal{L} = \boxed{\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)} + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

cT shifts hZZ coupling
and famously mZ.

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \boxed{\frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)} - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
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$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

cWW,cBB,cWB
renormalize gauge boson interactions and masses and induce hVV, hhVV interactions

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
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$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

cHL,cHL',cHE induce
Zee,Zhee,Zhhee contact interactions

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$

$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$

$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

Lastly, although c3W doesn't directly contribute to Zhh, it affects TGC measurements that determine other ops.

$$
\begin{aligned}
\Delta\mathcal{L} = & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
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& + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \boxed{\frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}} \\
& + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L) \\
& + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e) \ .
\end{aligned}
$$

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$$+\frac{g^2 c_{WW}}{\cdots} \quad \frac{4gg' c_{WB}}{\cdots}$$

9 EFT + c6 + 4 SM parameters

$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

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$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e) \ .$$

EWPT (LEP) + mh

	measured	σ	PDG SM fit
$\alpha^{-1}(m_Z)$	128.9220	(78)	same
G_F	1.1663787	(6)	same
m_Z	91.1876	(21)	91.1880
m_W	80.385	(15)	80.361
m_h	125.09	(24)	same
A_ℓ	0.1470	(13)	0.1480
$\Gamma(Z \to \ell^+\ell^-)$	83.385	(15)	83.995

Using these inputs, we can obtain a covariance matrix for 7 of our coefficients

$$\frac{\delta g}{g}\ ,\ \frac{\delta g'}{g'}\ ,\ \frac{\delta v}{v}\ ,\ \frac{\delta \lambda}{\lambda}\ ,\ c_T\ ,\ c_{HL}\ ,\ c_{HE}$$

with errors on single parameters at the 10^{-3} level.

e+e- > WW (TGC)

$$\Delta\mathcal{L}_{TGC} = ig_V\Big\{g_{1V}V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\Big\},$$

e+e- > WW physics is described by 3 independent coeffs, constraining 3 additional HEFT ops (cWB,cHL',c3W).

$$g_{1Z} = 1 + \frac{1}{c_0^2 - s_0^2}\left(-8\frac{s_0^2}{c_0^2}c_{WB} + \frac{1}{2}c_T - c'_{HL}\right),$$

$$\kappa_Z = g_{1Z} - 8\frac{s_0^2}{c_0^2}c_{WB}, \qquad \kappa_A = g_{1A}$$

$$\lambda_Z = xc_{3W}, \qquad \lambda_A = xc_{3W}$$

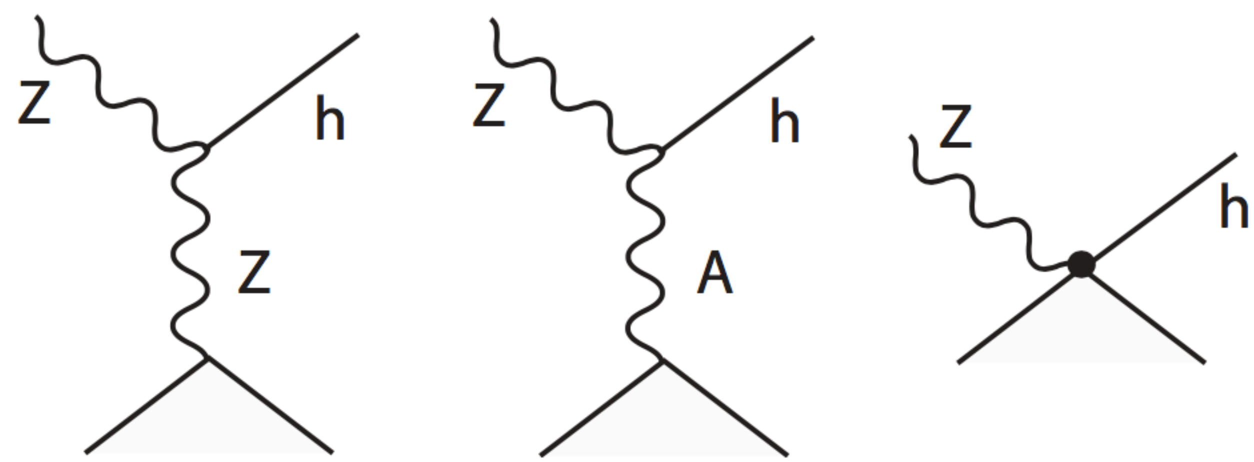
$$\begin{pmatrix} 7.7 & 5.6 & 3.0 \\ 5.6 & 7.6 & 2.8 \\ 3.0 & 2.8 & 15.6 \end{pmatrix} \times 10^{-4}$$

2/ab 250 GeV
Marchesini 2011

Single Higgs (LHC & Zh)

$$\Gamma(h \to \gamma\gamma) = \Gamma(h \to \gamma\gamma)_0 (1 + 528 s_w^2 (8c_{WW} - 2(8c_{WB}) + 8c_{BB}) + \cdots)$$

$$\Gamma(h \to \gamma Z) = \Gamma(h \to \gamma Z)_0 (1 + 290 s_w c_w (8c_{WW} - (1 - t_w^2)(8c_{WB}) - t_w^2 8c_{BB}) + \cdots)$$

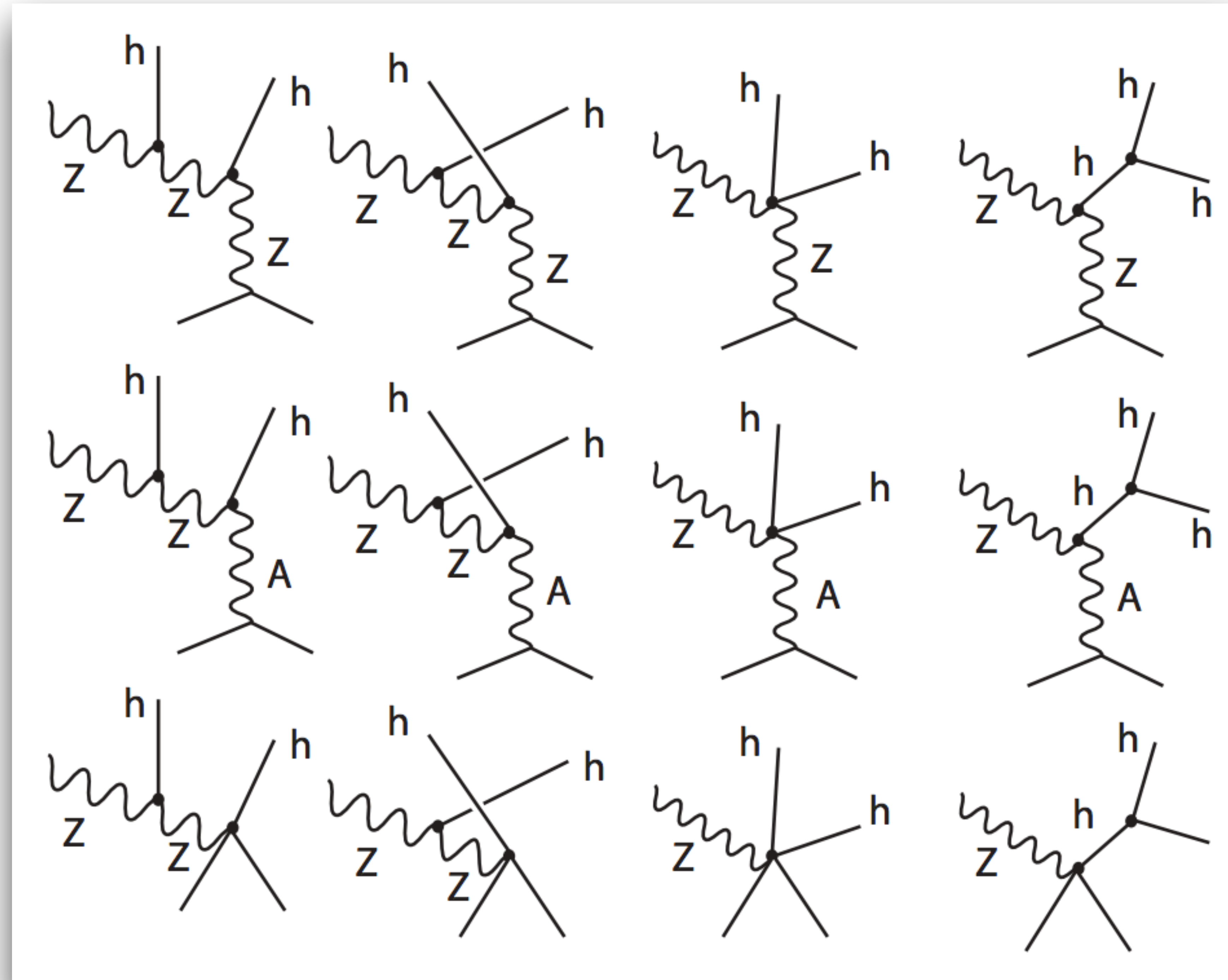


$$\mathcal{L} \ni \frac{m_Z^2}{v_0^2} \eta_Z h Z_\mu Z^\mu, \; \frac{\zeta_Z}{2} \frac{h}{v_0} Z_{\mu\nu} Z^{\mu\nu}, \; g_{eZh} (\bar{e}\gamma_\mu e) Z^\mu \frac{h}{v_0}$$

Three additional coefficients can be constrained to O(0.1%)

except for cH ~ O(1) % (see later)

Finally, e+e- > Zhh



Finally, e+e- > Zhh

$$\frac{\sigma(e^+e^- \to Zhh)}{SM} = 1 + \boxed{0.056 c_6} - 4.15 c_H + 15.1(8 c_{WW}) + \cdots$$
$$+62.1(c_{HL} + c'_{HL}) - 53.5 c_{HE}$$

After all, only c6 ~ 28% is possible (mostly stat only)

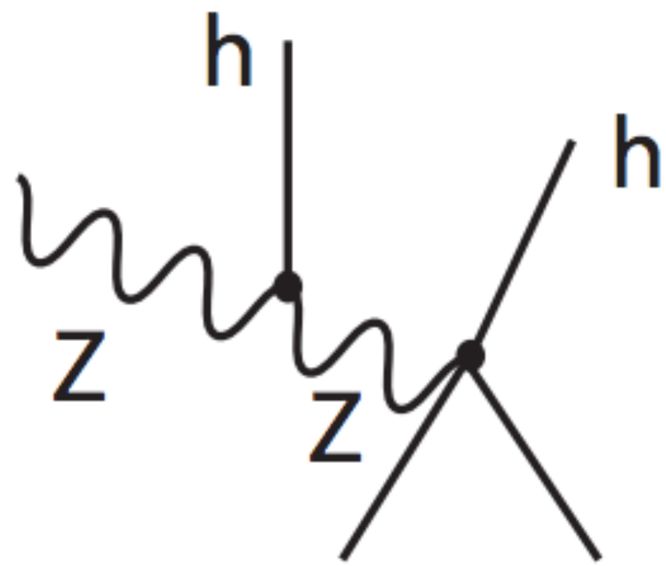
(e.g. ILC 500 2/ab).

Finally, e+e- > Zhh

$$\frac{\sigma(e^+e^- \to Zhh)}{SM} = 1 + \boxed{0.056 c_6} - 4.15 c_H + 15.1(8 c_{WW}) + \cdots$$
$$+62.1(c_{HL} + c'_{HL}) - 53.5 c_{HE}$$

Surprisingly,
there are several noisy contributions with large coefficients!

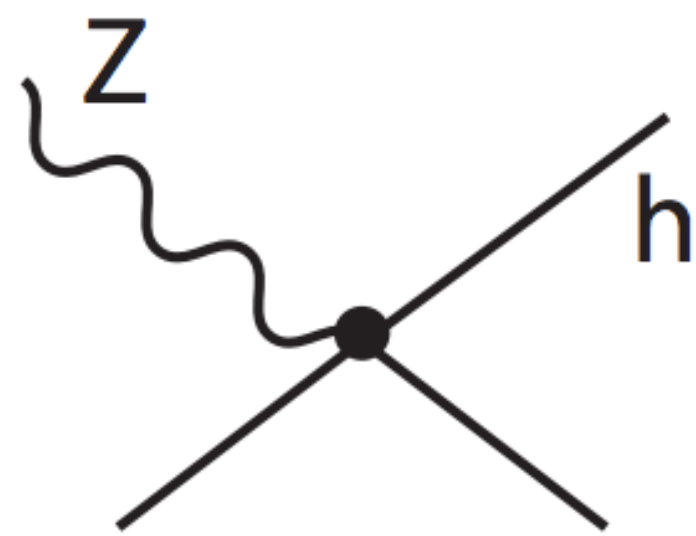
Challenge 1: s/mZ^2 enhancement



cHE, cHL, cHL' give contact-interaction contributions enhanced by s/mz^2 ~ 50 at 500 GeV.

To measure c6 at 1% level, these ops shall be measured at 0.01% level which is only marginally achieved at LEP EWPT.

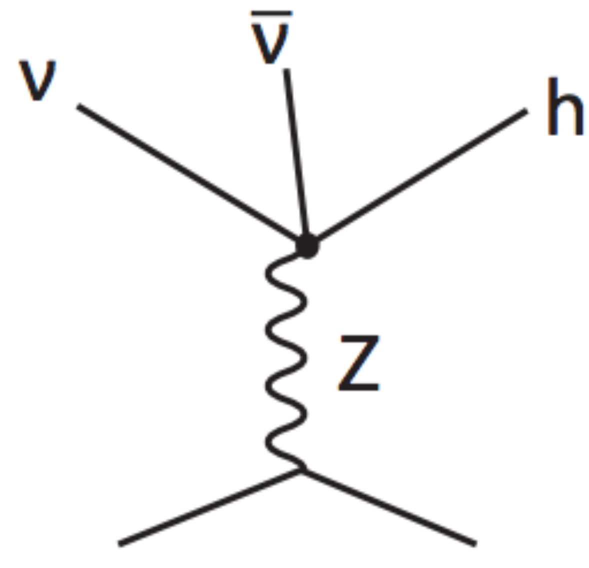
Challenge 2:
cH measurements from Zh



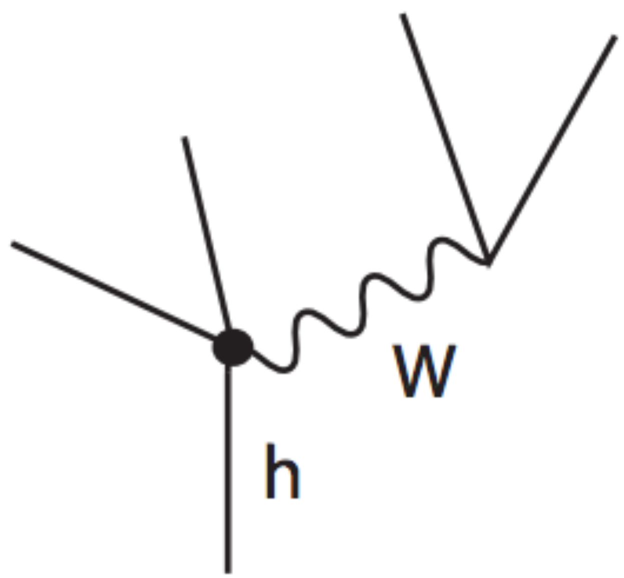
Similarly for e+e- > Zh, constraining cH.

LEP precisions on contact interactions lead to poor cH~1%

Fortunately, many other observables



VBF



h->WW*

$$\delta\Gamma(h \to b\bar{b}) = 1 - c_H + 2c_{b\Phi}$$

Many more observables
depending on additional HEFT parameters,
but many observables with different dependences.

Also, the enhancements at 250 GeV are less severe

	500 GeV		250 GeV
c_I	prec. EW	$+ Zh$	$+ Zh$
c_T	0.011	0.041	0.048
c_{HE}	0.043	0.040	0.047
c_{HL}	0.042	0.027	0.032
c'_{HL}	–	0.026	0.028
$8c_{WB}$	–	0.067	0.076
$8c_{BB}$	–	0.15	0.16
$8c_{WW}$	–	0.11	0.13
c_H	–	4.78	1.12

$$- \frac{(s - m_Z^2)}{2m_Z^2(s_w^2)} c_{HE}$$

Combining all systematically,

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

5% measurements (stat err only) of c6 is possible!

(e.g. ILC 250 + 500 + LHC)

General approach gives more than just adding all.

We can more reliably interpret and measure Higgs potential.

We can systematically identify challenges to be foremost importantly improved.

Thank you