EFT Fits for Triple Higgs Couplings at Lepton Colliders

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

Takehome messages

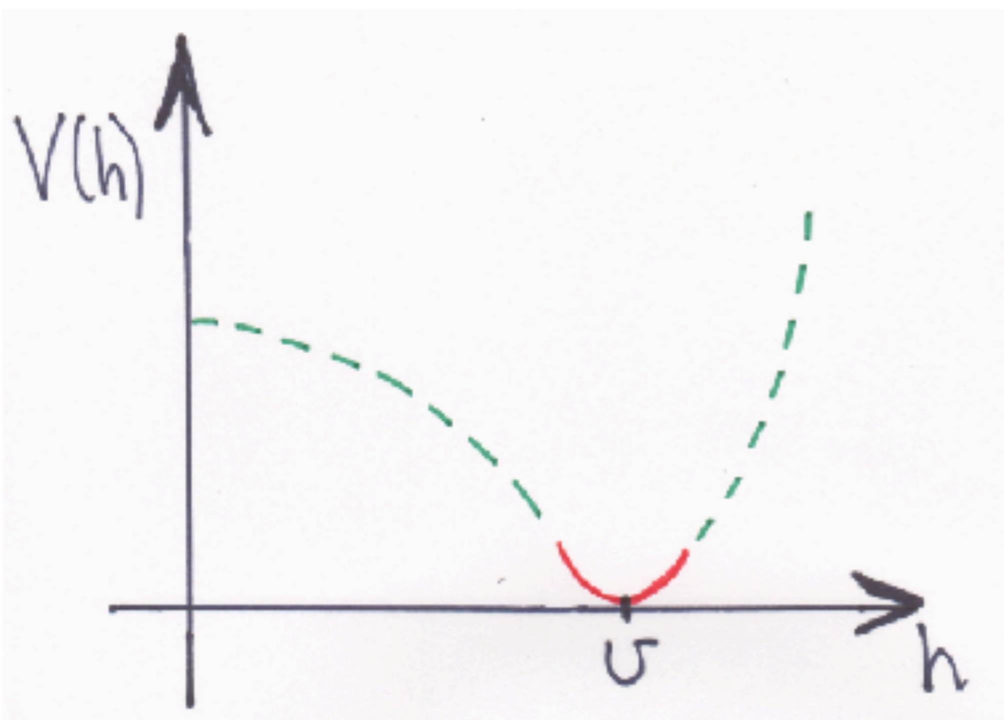
To measure Higgs potential deviations:

1. A general approach is needed and possible for unambiguous measurement. (Deviations mean a new physics, but which one?)

2. Best LEP EWPT observables are also sometimes NOT precise enough.

3. LHC, linear/circular e+e- can all do something good.

Higgs potential



by M.Perelstein

- What we know now:

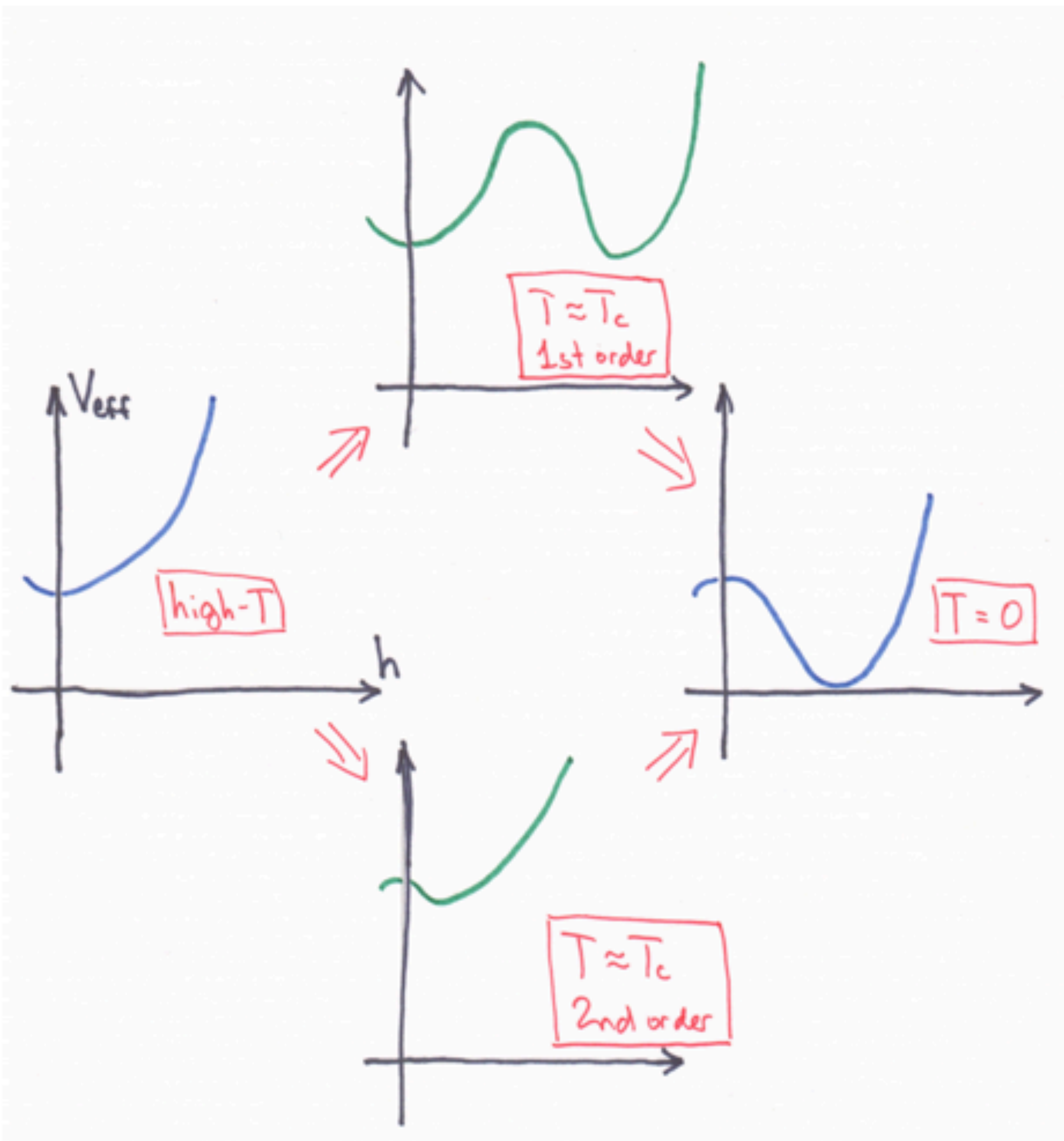
$$V'(h) = 0 \ @ \ h = v \approx 250 \text{ GeV}$$

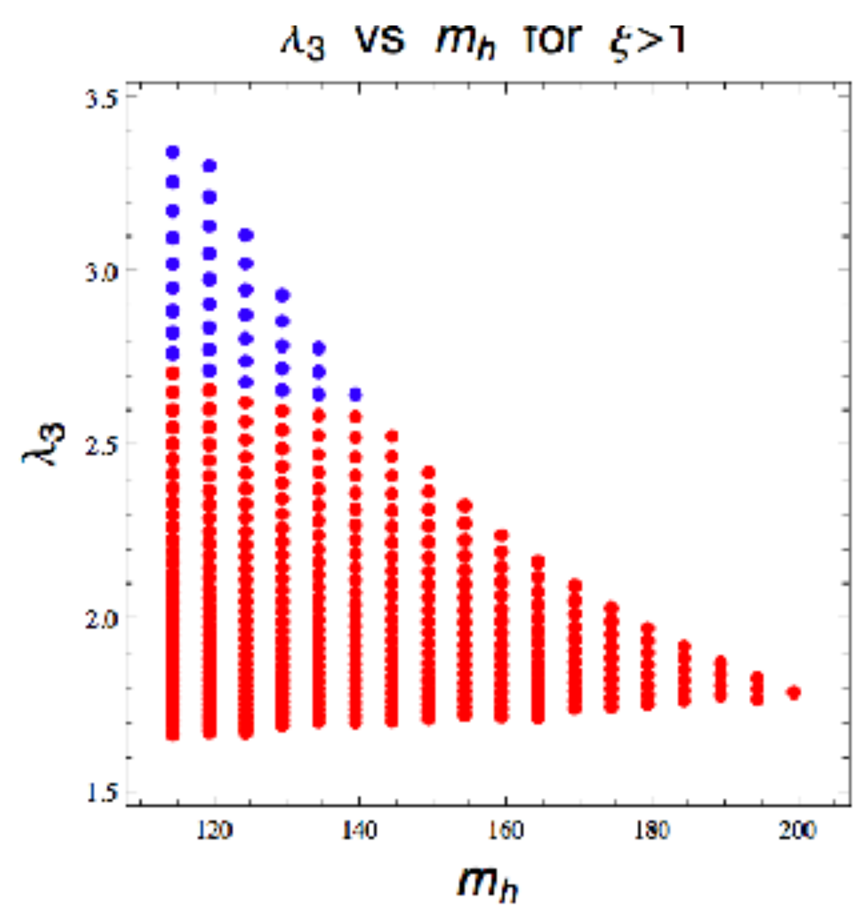
$$m_h^2 = V''(v), \ m_h \approx 125 \text{ GeV}$$

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

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

Probing EWPhT, hierarchy (and eventually early universe)

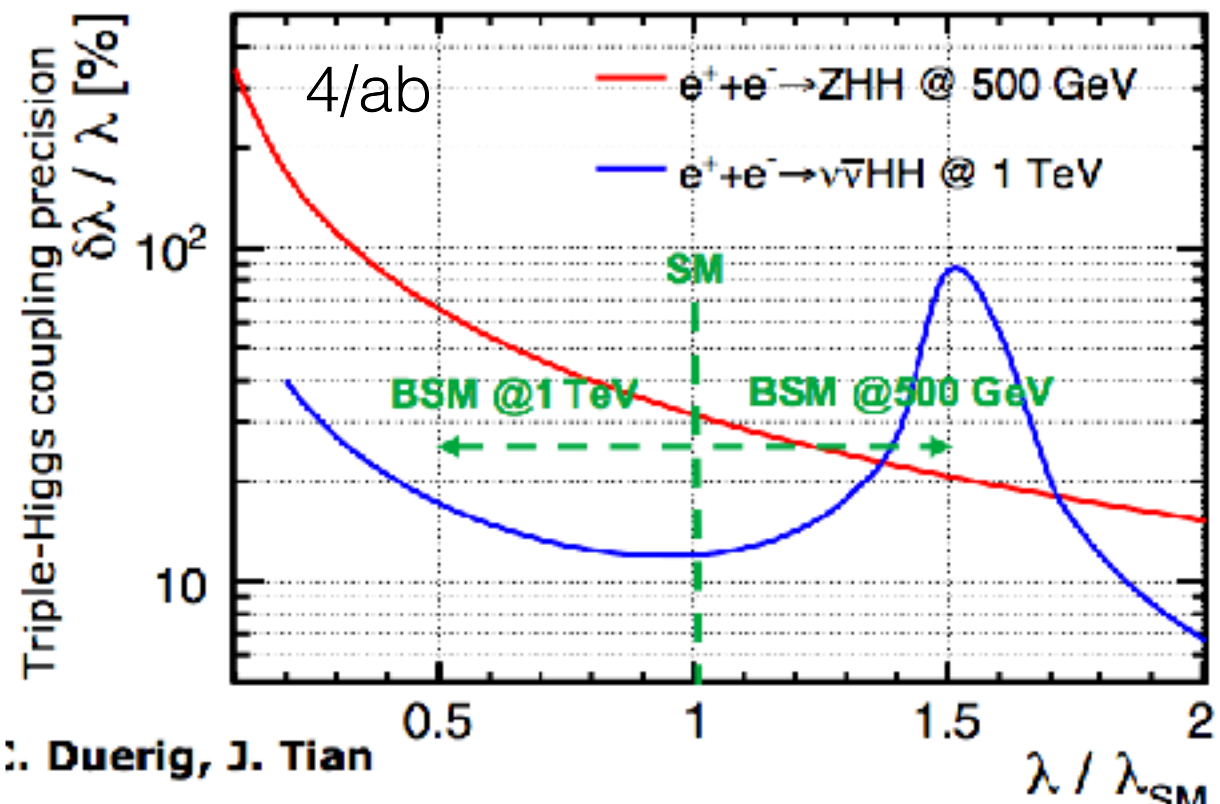




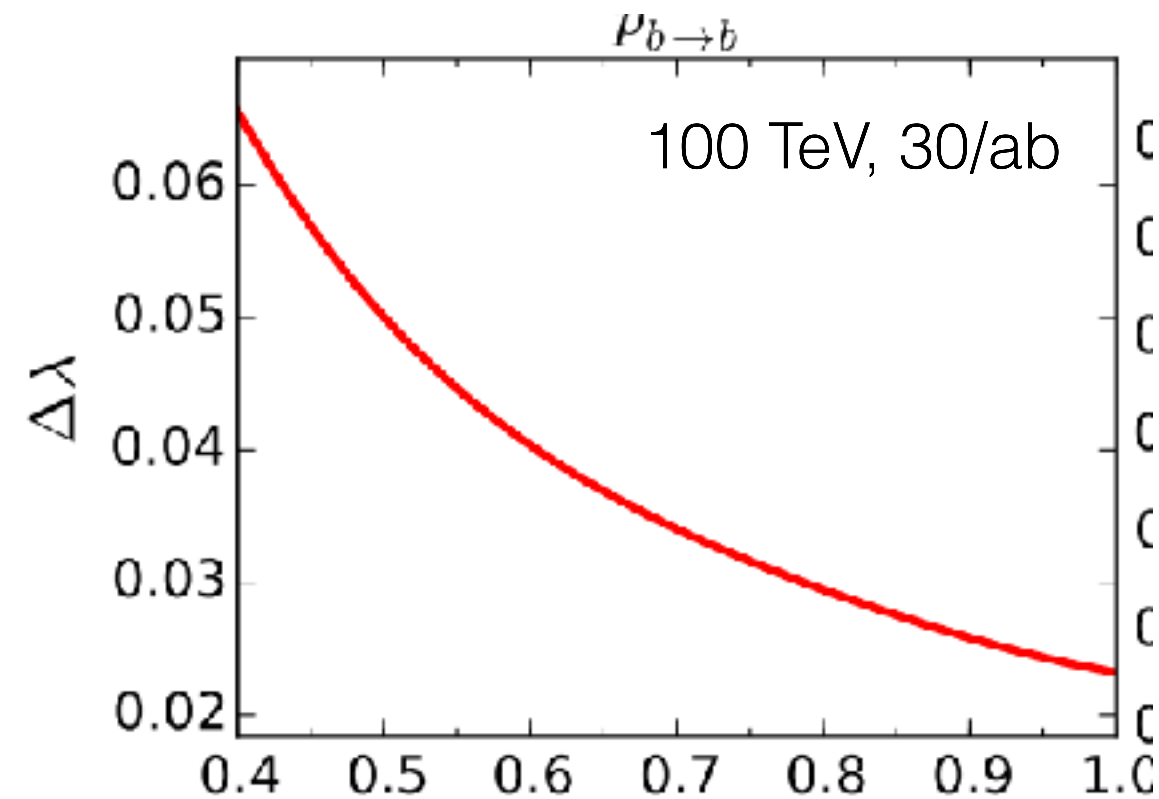
Plots from 0711.3018

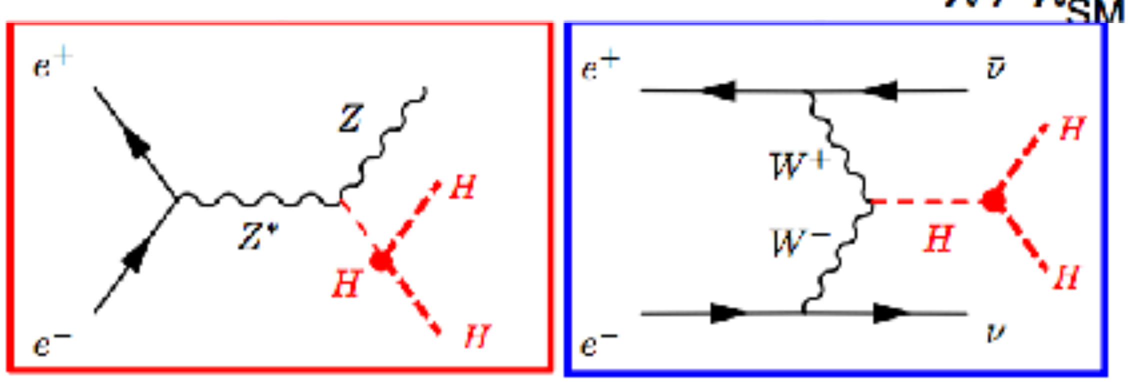
$$V = \mu^2|H|^2 + \lambda|H|^4 + \frac{1}{\Lambda^2}|H|^6$$

How we usually think about triple Higgs measurement

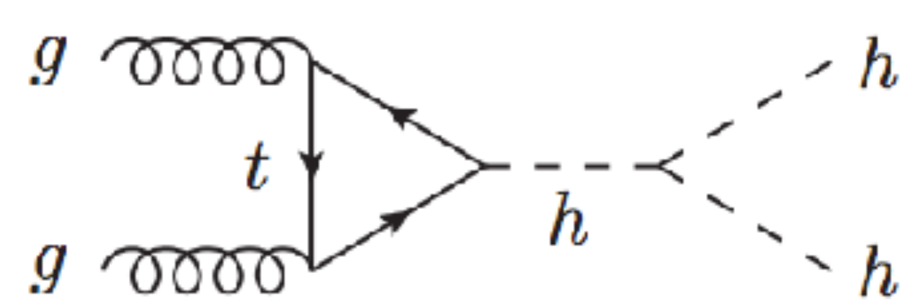


:. Duerig, J. Tian





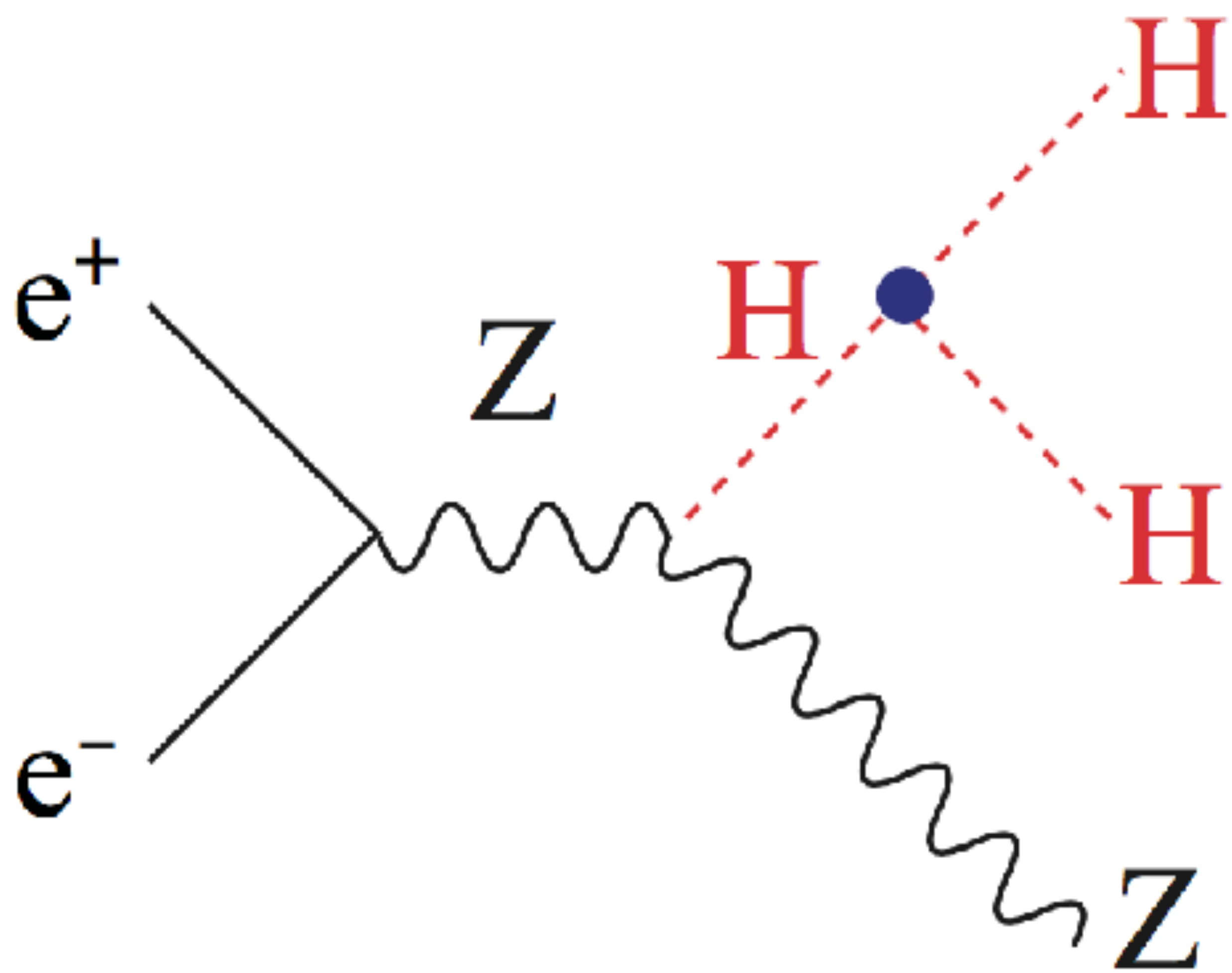
Diagrams with triple-Higgs coupling



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.

How shall we do?



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!

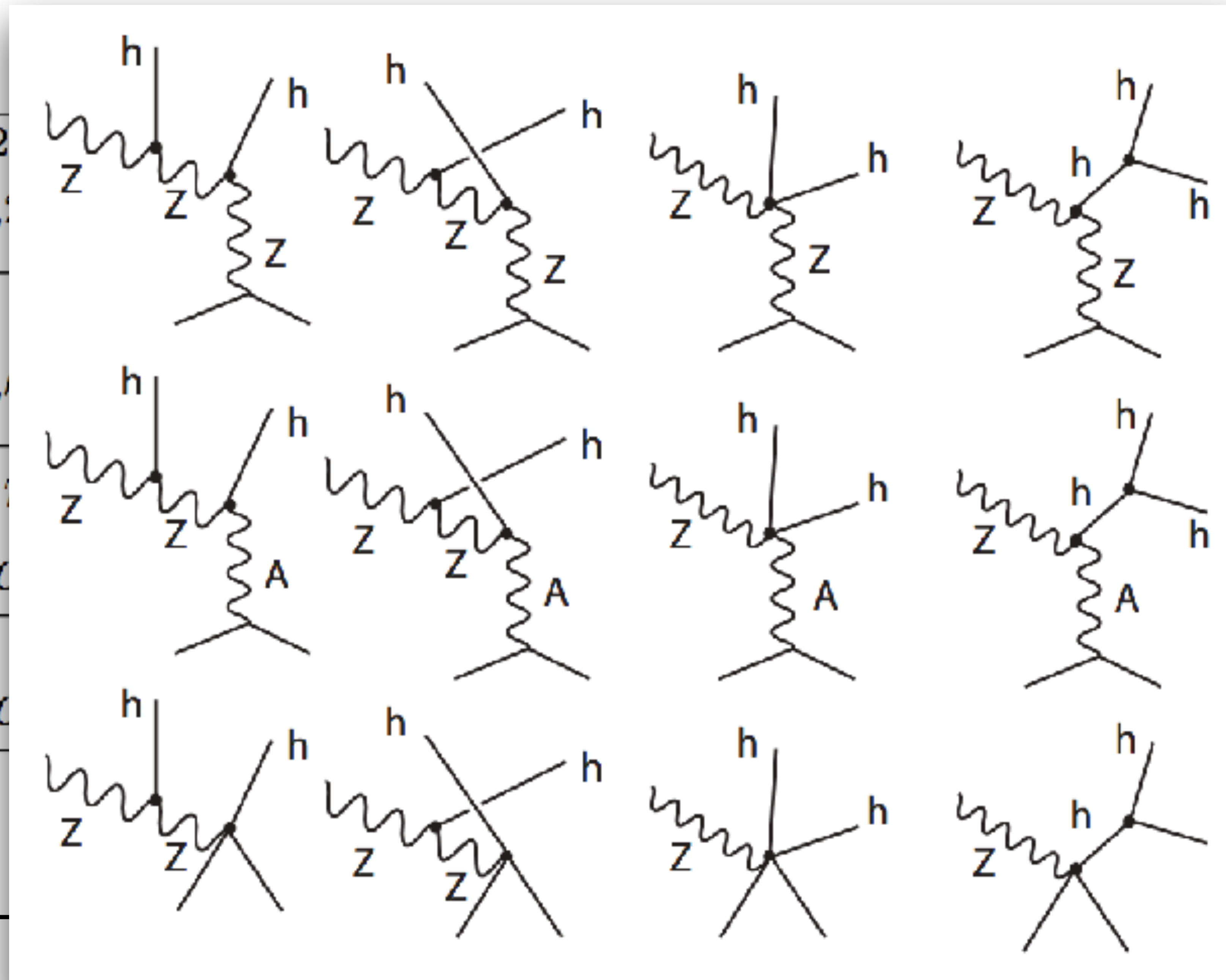
$$\Delta\mathcal{L} = \frac{c_H}{2v^2} \quad \cdots \quad - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$$+\frac{g'}{} \cdots$$

$$+\frac{g'}{} \cdots$$

$$+i\frac{c}{} \cdots \bar{L}\gamma_\mu t^a L)$$

$$+i\frac{c}{} \cdots$$



9 EFT … Zhh!

1 EFT op indirectly contribute to Zhh.

All 10 ops contribute!

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

How (well) can each of these be constrained?
Are these constraints good enough?
Or, what challenges and what need to be done?

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

9 EFT ops (+ SM parameters) contribute to Zhh!
1 EFT op indirectly contribute to Zhh.

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

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

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

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

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

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

cT shifts hZZ coupling
and famously mZ.

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

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

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

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

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

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

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

$$\boxed{\begin{aligned}&+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)\\ &+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .\end{aligned}}$$

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

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

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

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

9 EFT + c6 + 4 SM parameters

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

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

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

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.

NB: Interestingly, cWW and cBB cancel in these EWPT obs.

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

NB: Interestingly, cWW and cBB cancel out again!

LHC Single Higgs

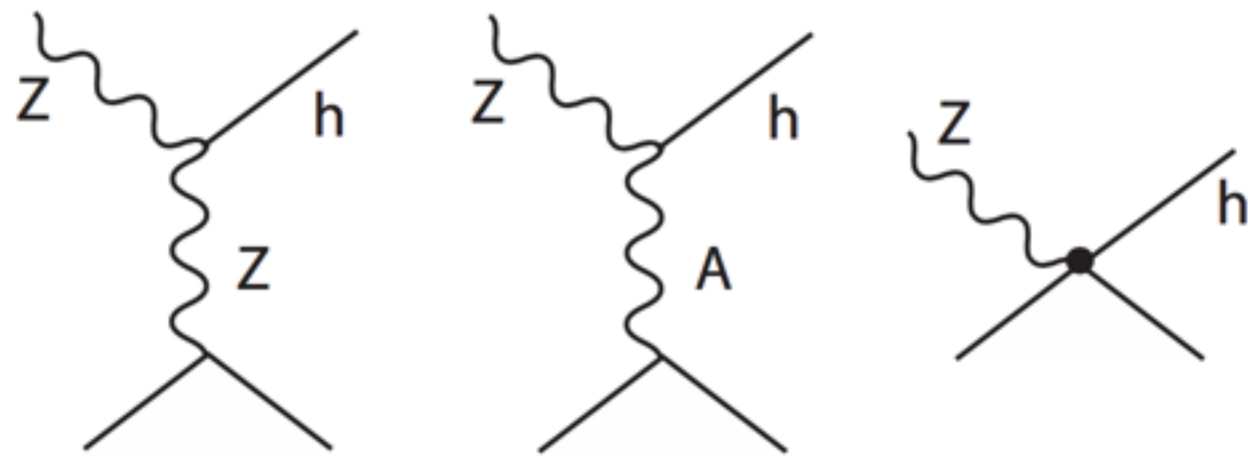
$$\Gamma(h \to \gamma\gamma) = \Gamma(h \to \gamma\gamma)_0 (1 + 528 s_w^2 (8c_{WW} - 2(8c_{WB}) + 8c_{BB}) + \cdots)$$

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

The ratios of BRs including gamma gamma, gamma Z, ZZ can be best measured at O(1-10)% at LHC.
(→ 2 more constraints: cWW and cBB finally.)

More precise and direct width measurements can be possible if combined with lepton collider total width.

e+e- > Zh

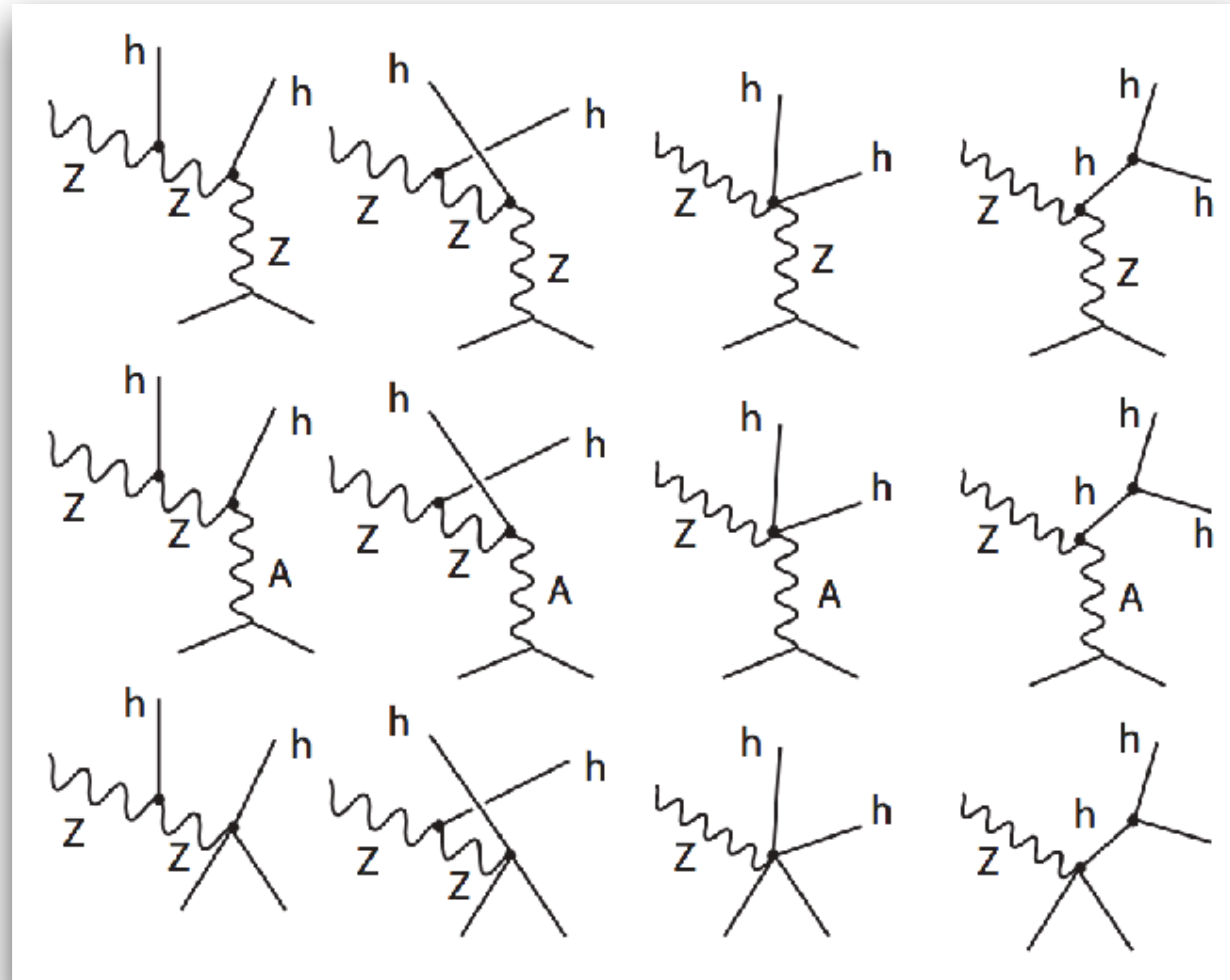


$$\mathcal{L} \ni \frac{m_Z^2}{v_0^2}\eta_Z h Z_\mu Z^\mu,\ \frac{\zeta_Z}{2}\frac{h}{v_0}Z_{\mu\nu}Z^{\mu\nu},\ g_{eZh}(\bar{e}\gamma_\mu e)Z^\mu\frac{h}{v_0}$$

After all, $\sigma(e^+e^- \to Zh)$ is another function of c_H, c_{WW}, c_{BB}

By combining the two single Higgs measurements, the three coefficients can be constrained to O(0.1%) except for cH ~ O(1) % (see later).

Finally, e+e- > Zhh



Finally, e+e- > Zhh

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

Surprisingly, in addition to the well-known c6 dependence,

there are several contributions with large coefficients!

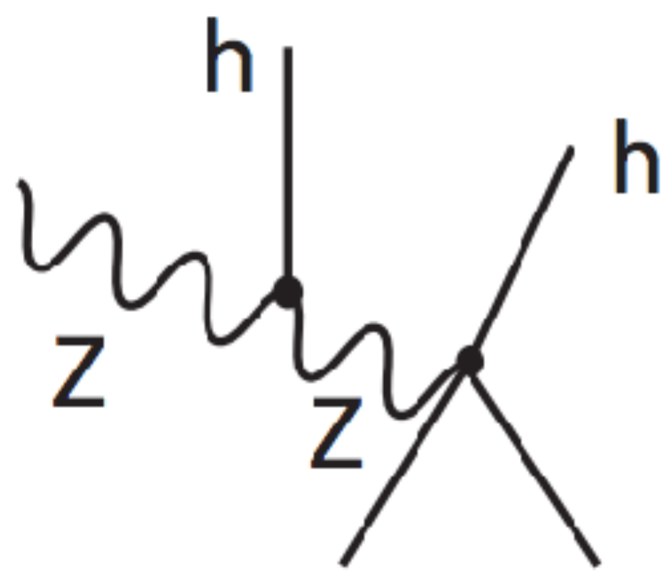
Finally, e+e- > Zhh

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

A	$[< A^2 >]^{1/2}$	A	$[< A^2 >]^{1/2}$
c_H	4.8	$(c_{HL} + c'_{HL})$	0.048
$(8c_{WW})$	0.11	c_{HE}	0.040
$(-4.15c_H + 15.1(8c_{WW}))$	21	$62.1(c_{HL} + c'_{HL}) - 53.5c_{HE}$	4.9

After all, only c6 ~ 28% is possible (mostly stat only)
(e.g. ILC 500 2/ab).

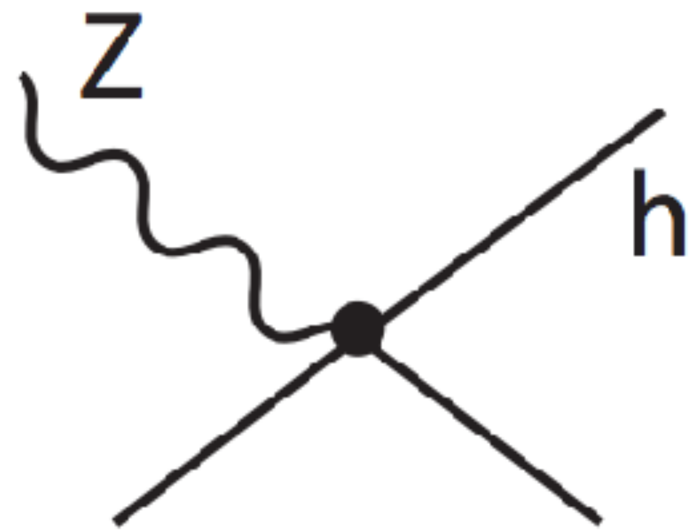
Challenge 1: s/mZ^2 enhancement



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.

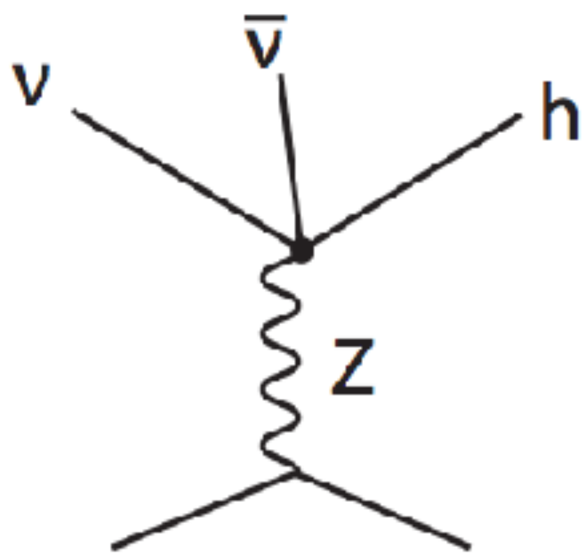
Challenge 2: cH measurements from Zh



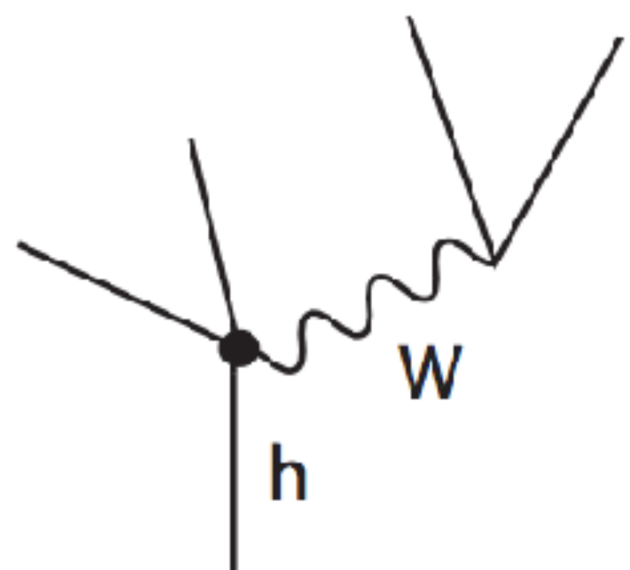
The e+e- > Zh, constraining cH, also suffers from the same s/mz^2 enhancement. LEP precisions on cHL etc leads to poor cH~1%

$$\frac{(s-m_Z^2)}{2m_Z^2(1/2-s_w^2)}(c_{HL}+c'_{HL}) \qquad -\frac{(s-m_Z^2)}{2m_Z^2(s_w^2)}c_{HE}$$

Fortunately, we have other single Higgs obs



VBF



h->WW*

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

Many more observables (particularly from LHC and 500 e+e-).
They depend on additional HEFT parameters
as well as the same enhancement.

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	–	$\boxed{4.78}$	$\boxed{1.12}$

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

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)

What have we combined?

- Beam polarization: cHE vs. cHL, cHL', finer handle.
- Luminosity: sqrt{N} improvement.
- Energy: Bigger sensitivity to s/mz^2 enhancement, and new channels such as VBF.
- LHC: many single Higgs observables, available early on.

Each lead to similar deg of resolution to the s/mZ^2 issue.
All have pros and cons. No single one is best.
Might be better ideas too.

General approach gives more than just adding all.

Considering all ops is not just adding
all the small errors propagated.

If the results turn out to be not good enough,

we can systematically identify
which parameter and which observables
to be foremost importantly improved.

Takehome messages

0. Deviations from the SM Higgs potential means a new physics.

1. Only a general approach allows unambiguous measure, interpret and sys improvement.

2. Best LEP EWPT observables are also often not precise enough.

3. LHC, ILC/CEPC can all do something good.

Thank you

and

let's do our best for future colliders