BSM primary effects

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$\mathcal{L}_6$ (dimension-six operators) ➡ Leading BSM effects

parametrized by **Wilson coefficients**: c_{WW} , c_{BB} , c_W , …

Good for model-building (e.g. SILH), but…

not a clear **connection** with physics!

Then, better talk about **couplings** (interactions)!

couplings ≈ observables e.g. $g^{Z}_{ff} \leftrightarrow \Gamma(Z \to ff)$

➥ **BSM primaries**

(a proposal to **parametrize** BSM effects)

arXiv:1405.0181

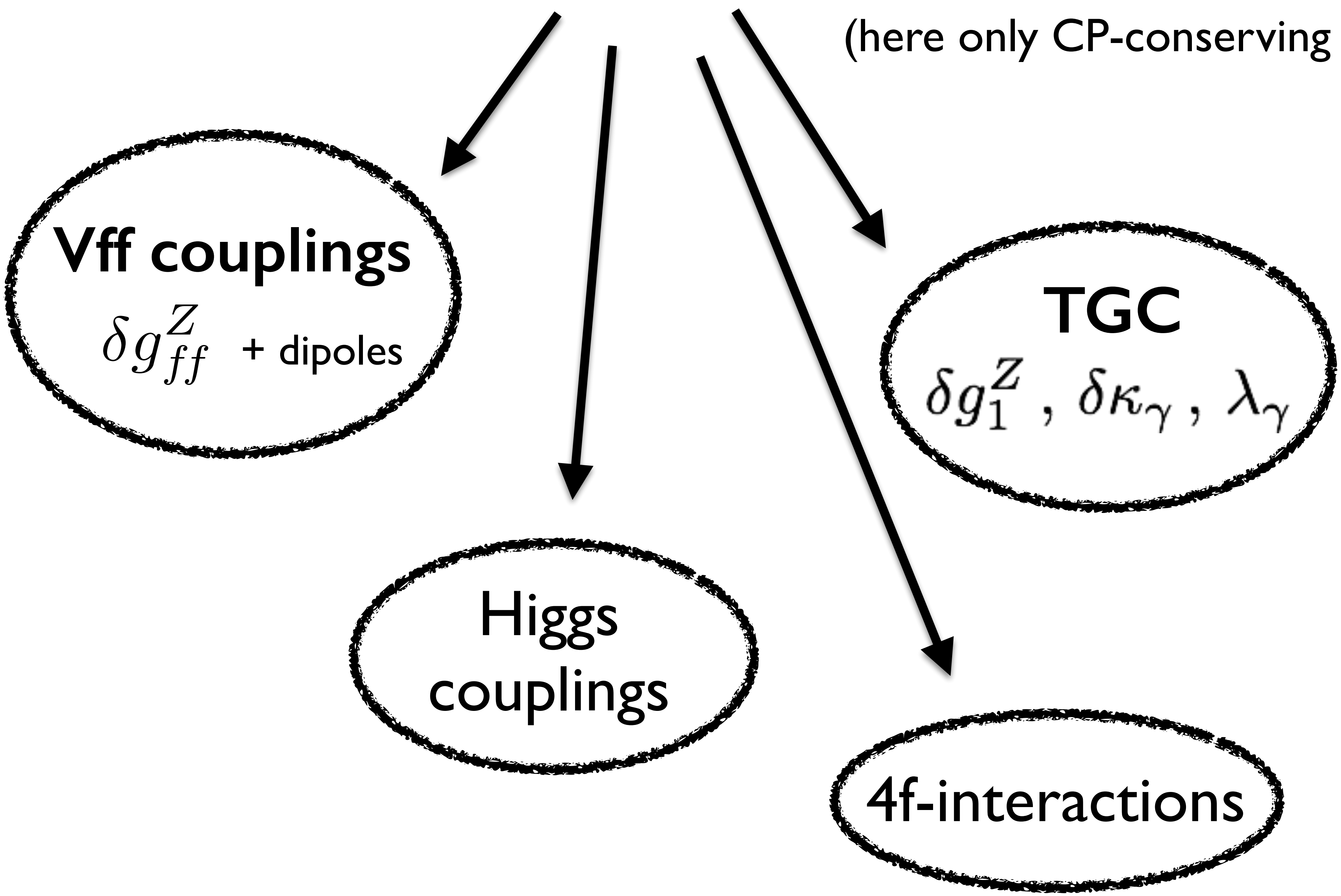
contributions to physical couplings!

- ➥ **Not all type of interactions can arise from $\mathcal{L}_6$!**
- ➥ **Plenty of correlations among possible interactions**

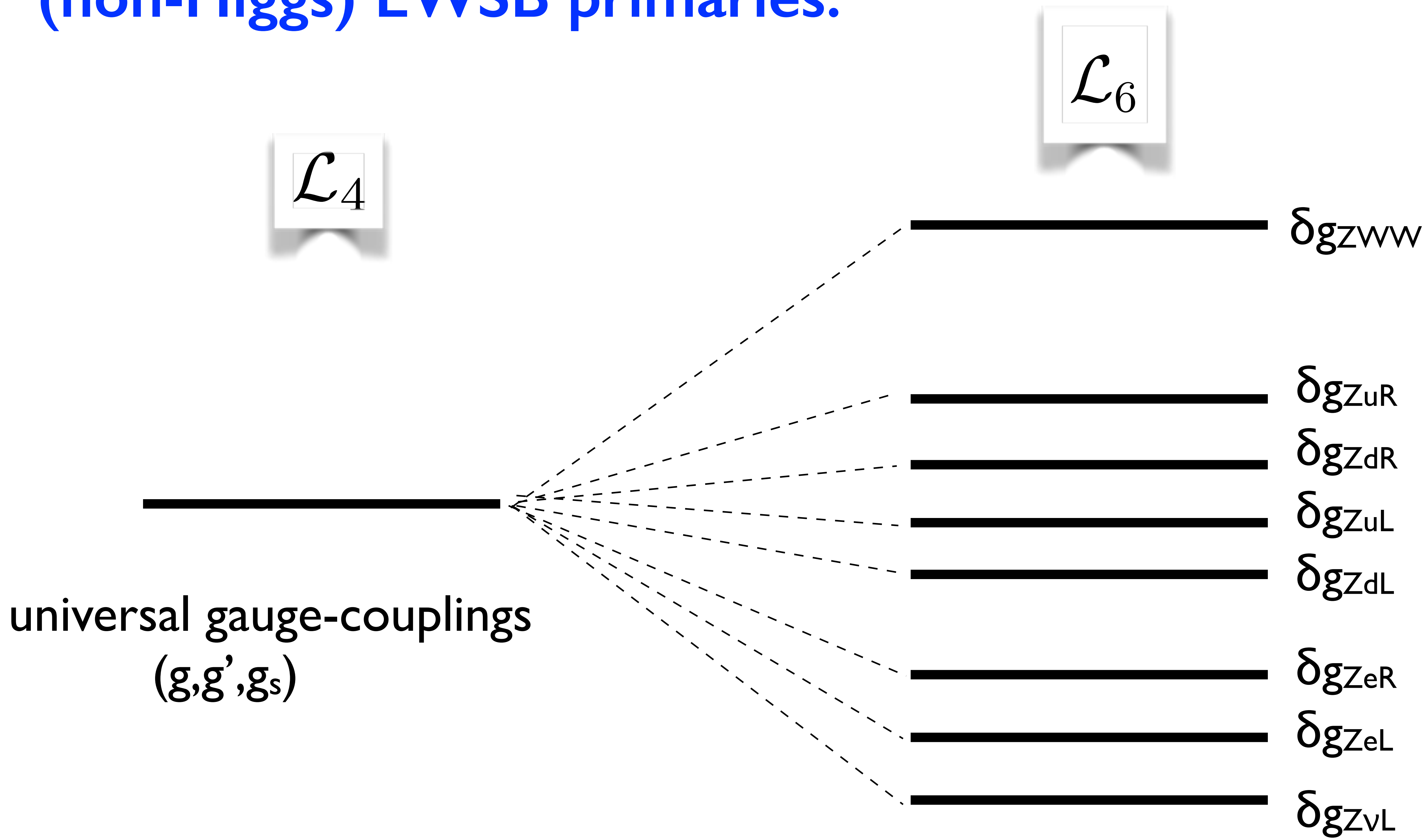
(see also arXiv:1406.6376)

BSM primaries = Best-measured <u>independent</u> couplings

(here only CP-conserving for simplicity)



(non-Higgs) EWSB primaries:



+ dipole-type interactions for W & f

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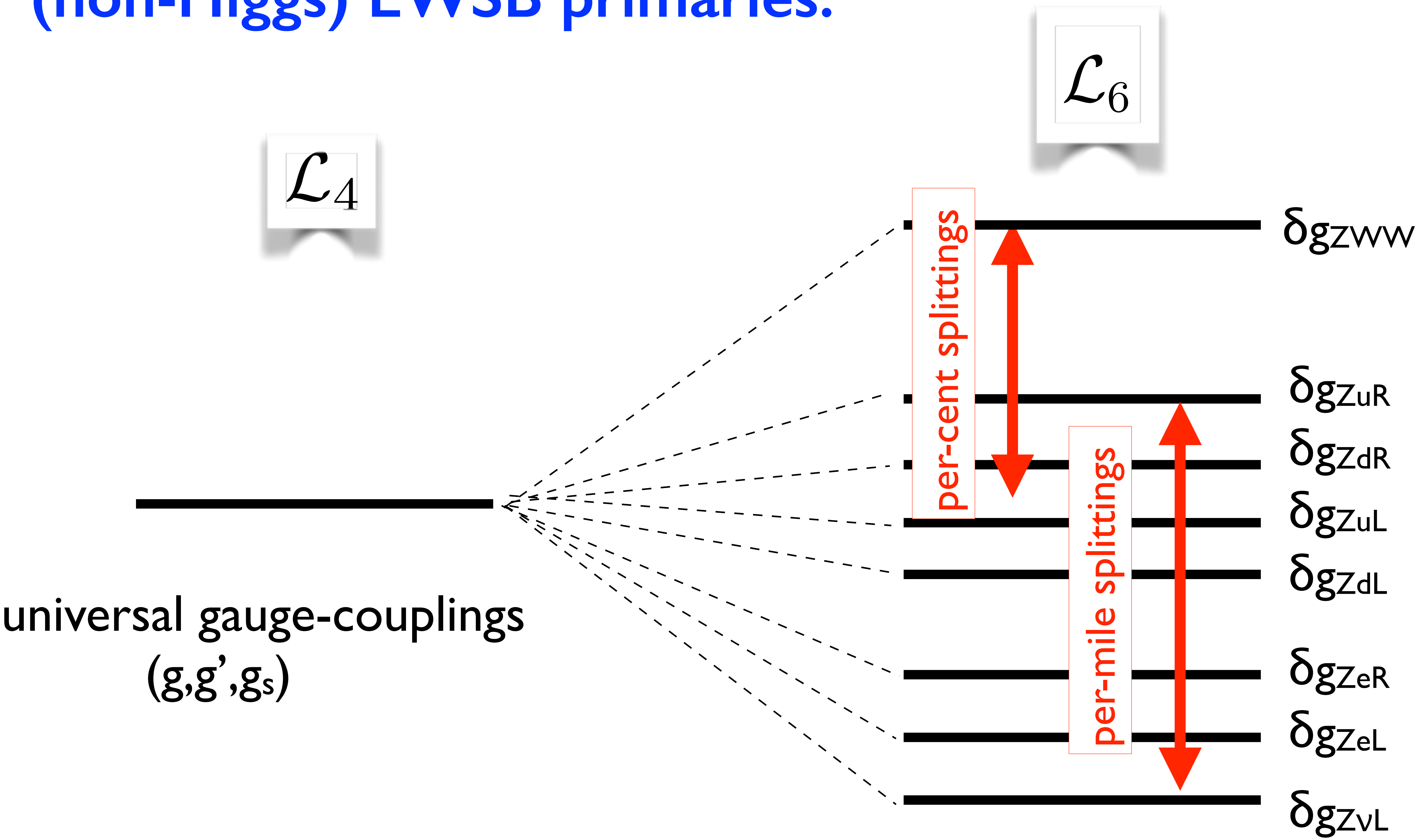

+ dipole-type interactions for W & f

Higgs couplings

$O(h^3)$, $O(h\partial^2 V^2)$ and $O(hVf^2)$

All relevant couplings for *single* Higgs physics:

$$\mathcal{L}_h^{\text{primary}} = g^h_{VV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \frac{1}{6}\, g_{3h}\, h^3 + g^h_{ff}\,\left(h \bar{f}_L f_R + h.c.\right)$$
$$+ \kappa_{GG}\,\frac{h}{2v} G^{A\,\mu\nu} G^A_{\mu\nu} + \kappa_{\gamma\gamma}\,\frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma}\frac{h}{v} A^{\mu\nu} Z_{\mu\nu}\,,$$

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + g^h_{Zff}\,\frac{h}{2v}\,\left(Z_\mu J^\mu_N + h.c.\right) + g^h_{Wff'}\,\frac{h}{v}\,\left(W^+_\mu J^\mu_C + h.c.\right)$$
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Higgs couplings

$O(h^3)$, $O(h\partial^2 V^2)$ and $O(hVf^2)$

independent from others

$$\mathcal{L}_h^{\text{primary}} = g^h_{VV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \frac{1}{6}\, g_{3h}\, h^3 + g^h_{ff}\, \left(h\bar{f}_L f_R + h.c.\right)$$
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correlated to other couplings

8 Primary Higgs couplings

(assuming CP-conservation)

$$
\begin{aligned}
\mathcal{L}_h^{\text{primary}} = \; & g^h_{ff}\, h \bar{f}_L f_R + h.c. \qquad (f = b, \tau, t) \\
& + g^h_{VV}\, h \left[W^{+\,\mu} W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu \right] \\
& + \kappa_{GG} \frac{h}{2v} G^{\mu\nu} G_{\mu\nu} \\
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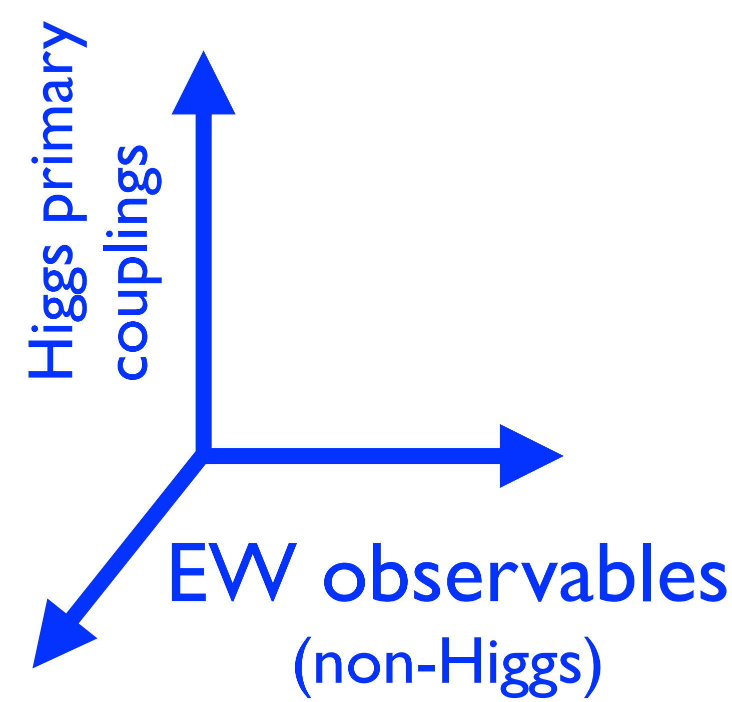
& + \frac{1}{6} g_{3h} h^3
\end{aligned}
$$



8 Primary Higgs couplings

(assuming CP-conservation)

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$$+ g_{VV}^h h \left[W^{+\mu} W_\mu^- + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu \right]$$

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$$+ \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}$$

$$+ \frac{1}{6} g_{3h} h^3$$

6 measured at the LHC (the "kappas"): g_{ff}^h, g_{VV}^h, κ_{GG}, $\kappa_{\gamma\gamma}$

$\kappa_{Z\gamma}$ → **bounds from h→Zγ**

g_{3h} → **Affects h^3: It can be measured in the far future by GG→hh**

Expected largest corrections to Higgs couplings:

	hff	hVV	hγγ	hγZ	hGG	h
MSSM	√					√
NMSSM	√	√	√	√	√	√
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

Beyond the primary Higgs couplings

Beyond the primary Higgs couplings

custodial breaking hVV

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\, h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$$

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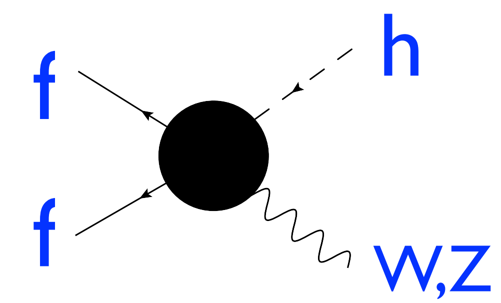
contact interactions



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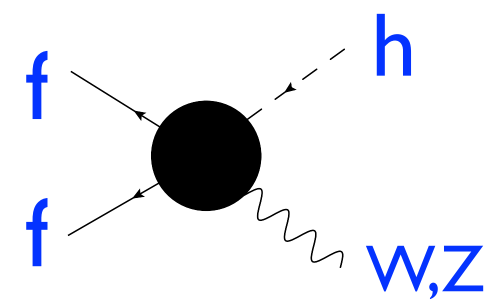
contact interactions

momentum-dependent
hVV couplings



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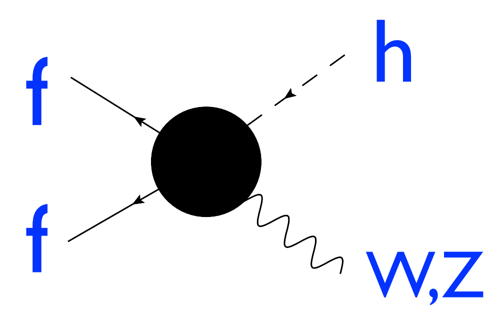
momentum-dependent hVV couplings



➥ **I find this to be best parametrization to go beyond the "kappa's approach"**

Beyond the primary Higgs couplings

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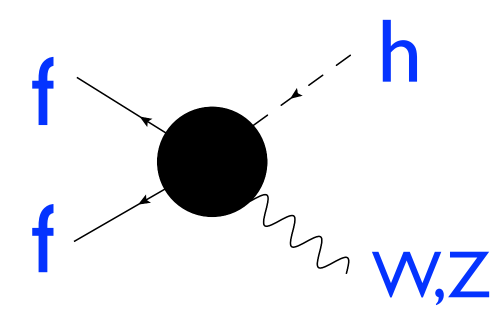

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but remember BSM effects here are <u>not</u> independent from effects to other couplings!

All can be written as a function of contributions to other couplings:

$$\delta g^h_{ZZ} = 2g t^2_{\theta_W} m_W \left(c^2_{\theta_W} \delta g^Z_1 - \delta\kappa_\gamma\right) ,$$

$$\delta g^W_{ff'} = \frac{c_{\theta_W}}{\sqrt{2}} \left(\delta g^Z_{ff} V_{\rm CKM} - V_{\rm CKM} \delta g^Z_{f'f'}\right) \quad \text{for} \quad f = f_L$$

$$g^h_{Zff} = 2\delta g^Z_{ff} - 2\delta g^Z_1 (g^Z_{ff} c_{2\theta_W} + g^\gamma_{ff} s_{2\theta_W}) + 2\delta\kappa_\gamma Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}} ,$$

$$g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_{ff'} c^2_{\theta_W} ,$$

$$\kappa_{ZZ} = \frac{1}{c^2_{\theta_W}} \delta\kappa_\gamma + 2\frac{c_{2\theta_W}}{s_{2\theta_W}} \kappa_{Z\gamma} + \kappa_{\gamma\gamma} ,$$

$$\kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + \kappa_{\gamma\gamma} ,$$

Zff couplings
δg^Z_{ff}

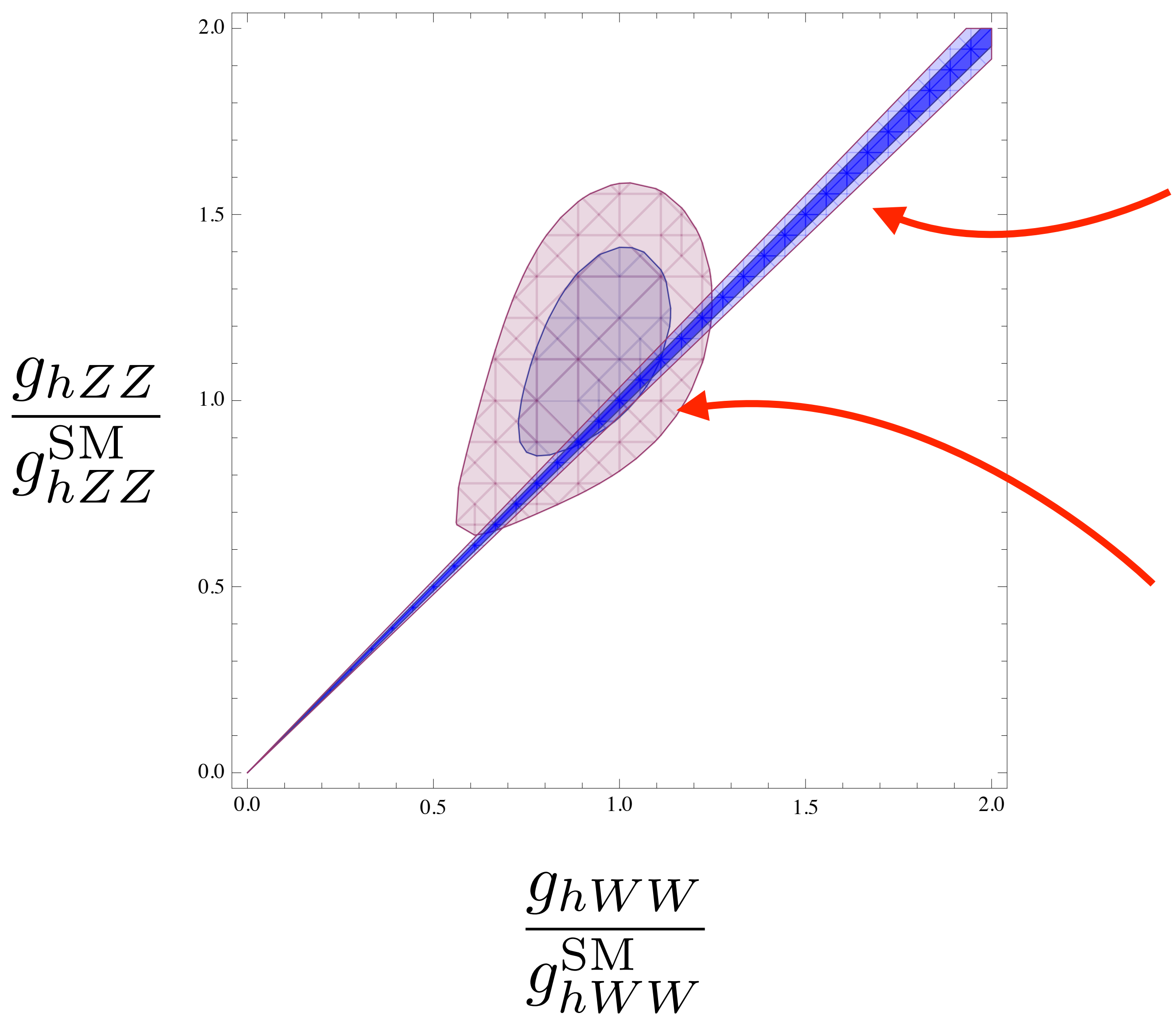
Higgs primary couplings
$\kappa_{\gamma\gamma}$, $\kappa_{Z\gamma}$

TGC
δg^Z_1 , $\delta\kappa_\gamma$

Proposal (for the future):

try to measure **all** Higgs couplings and **compare** with other non-Higgs "observables"

What I would like to see:



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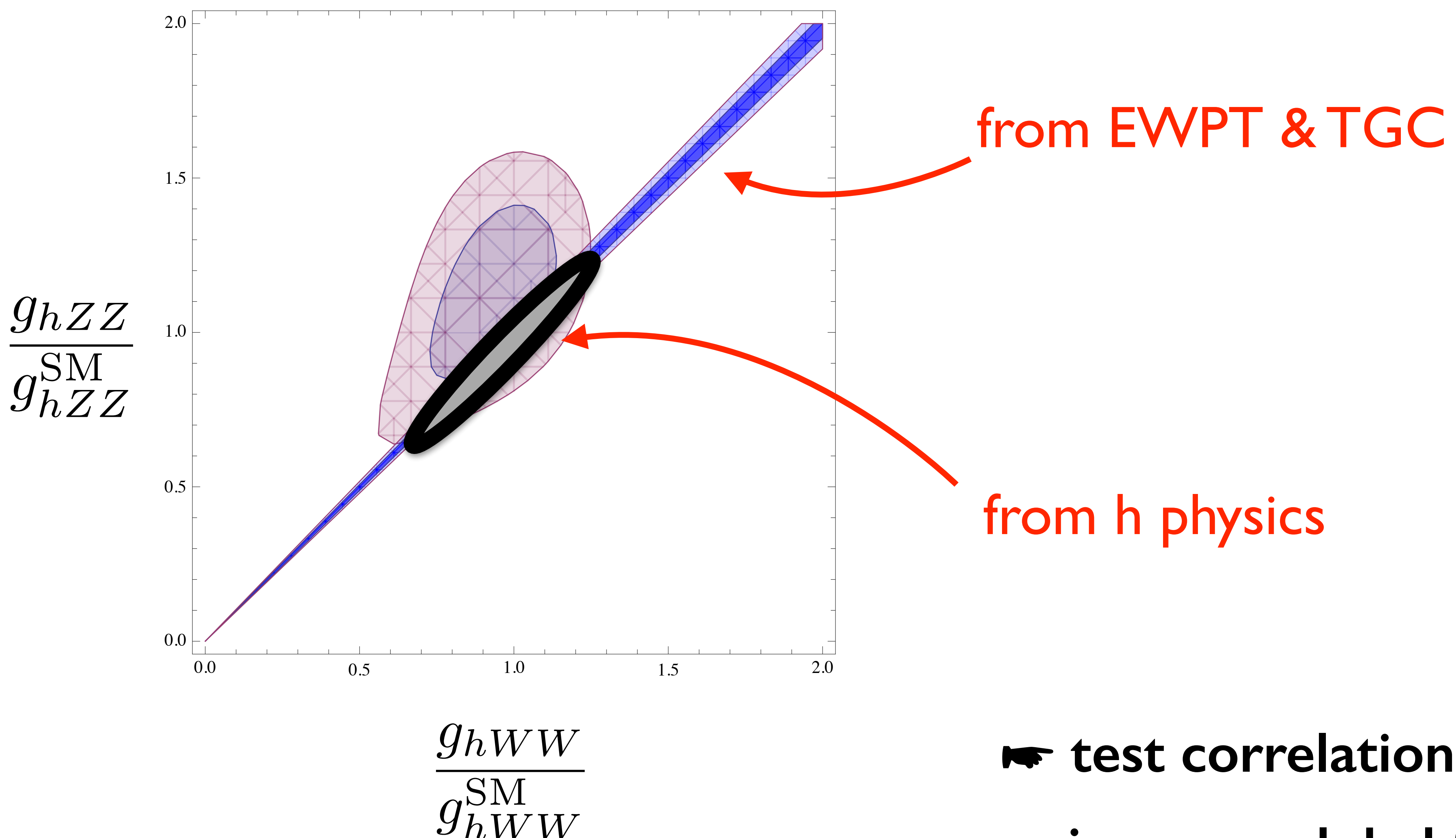
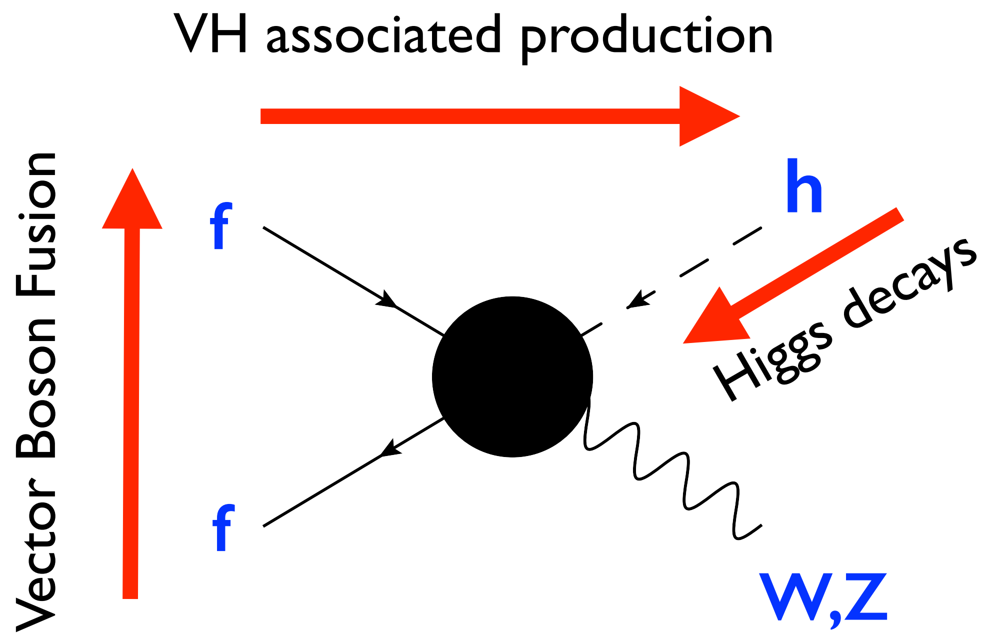


☛ **test correlations** √

☛ **improve global fit of primaries** √

Non-primary Higgs couplings can be disentangled in distributions:



$$\mathcal{M}_{hVff}(q,p) = \frac{1}{v}\epsilon^{*\mu}(q)\, J_V^{\nu}(p)\left[A^V\,\eta_{\mu\nu} + B^V\,(p\cdot q\,\eta_{\mu\nu} - p_\mu\, q_\nu) + C^V\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

$$A^V = a^V + \widehat{a}^V\frac{m_V^2}{p^2 - m_V^2}\,, \qquad B^V = b^V\frac{1}{p^2-m_V^2} + \widehat{b}^V\frac{1}{p^2}$$

one-to-one correspondence with Higgs couplings

$\mathbf{hV_\mu J^\mu}$ $\quad$ $\mathbf{hV^\mu V_\mu}$ $\quad$ $\mathbf{hV^{\mu\nu}V_{\mu\nu}}$ $\quad$ $\mathbf{hZ^{\mu\nu}A_{\mu\nu}}$

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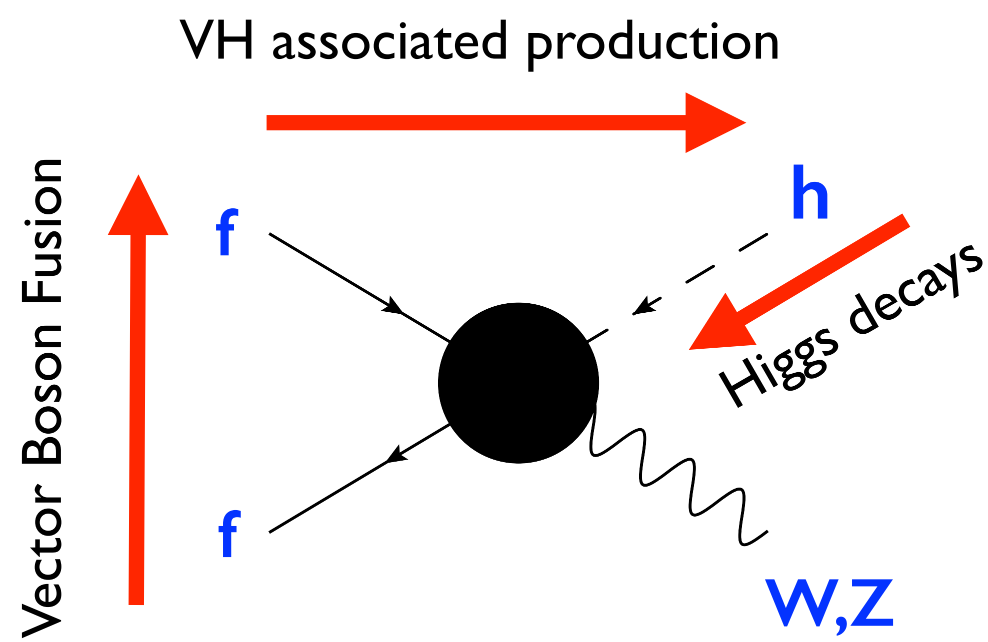

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one-to-one correspondence
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- $\mathbf{hV_\mu J^\mu}$
- $\mathbf{hV^\mu V_\mu}$
- $\mathbf{hV^{\mu\nu} V_{\mu\nu}}$
- $\mathbf{hZ^{\mu\nu} A_{\mu\nu}}$

dominant at high-energy!

Priorities (non-democratic approach: Not all couplings are equal(ly) interesting):

We must decide first which
are the best set of couplings to measure

Reduction of couplings **must be** either by

1) Symmetries
2) Dynamics (of the new-physics sector)

A **proposal** for non-primaries:

☛ Keep lowest-order in a q^2-expansion

☛ Impose universality and custodial


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NO UNAUTHORIZED PERSONNEL
BEYOND THIS POINT

Correlations between couplings

Explicit correlations between hZff and Zff:

arXiv:1405.0181
arXiv:1406.6376

$$\hat{h} \equiv v + h$$

appear combined in the same operators

$$\Delta\mathcal{L}_{qq}^{V} = \boldsymbol{\delta g_{uR}^{Z}} \frac{\hat{h}^2}{v^2} Z^\mu \bar{u}_R \gamma_\mu u_R + \boldsymbol{\delta g_{dR}^{Z}} \frac{\hat{h}^2}{v^2} Z^\mu \bar{d}_R \gamma_\mu d_R$$
$$+ \boldsymbol{\delta g_{dL}^{Z}} \frac{\hat{h}^2}{v^2} \left[Z^\mu \bar{d}_L \gamma_\mu d_L - \frac{c_{\theta_W}}{\sqrt{2}} (W^{+\mu} \bar{u}_L \gamma_\mu d_L + \mathrm{h.c.}) \right]$$
$$+ \boldsymbol{\delta g_{uL}^{Z}} \frac{\hat{h}^2}{v^2} \left[Z^\mu \bar{u}_L \gamma_\mu u_L + \frac{c_{\theta_W}}{\sqrt{2}} (W^{+\mu} \bar{u_L} \gamma_\mu d_L + \mathrm{h.c.}) \right]$$

$$\Delta\mathcal{L}_{ee}^{V} = \boldsymbol{\delta g_{eR}^{Z}} \frac{\hat{h}^2}{v^2} Z^\mu \bar{e}_R \gamma_\mu e_R$$
$$+ \boldsymbol{\delta g_{eL}^{Z}} \frac{\hat{h}^2}{v^2} \left[Z^\mu \bar{e}_L \gamma_\mu e_L - \frac{c_{\theta_W}}{\sqrt{2}} (W^{+\mu} \bar{\nu_L} \gamma_\mu e_L + \mathrm{h.c.}) \right]$$
$$+ \boldsymbol{\delta g_{\nu L}^{Z}} \frac{\hat{h}^2}{v^2} \left[Z^\mu \bar{\nu}_L \gamma_\mu \nu_L + \frac{c_{\theta_W}}{\sqrt{2}} (W^{+\mu} \bar{\nu_L} \gamma_\mu e_L + \mathrm{h.c.}) \right]$$

Correlations with the primary Higgs couplings:

arXiv:1405.0181
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hVV form-factor correlated with hγγ

$$\Delta\mathcal{L}^h_{\gamma\gamma} = \boldsymbol{\kappa_{\gamma\gamma}}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[A_{\mu\nu}A^{\mu\nu}+Z_{\mu\nu}Z^{\mu\nu}+2W^+_{\mu\nu}W^{-\mu\nu}\right]$$

$$\Delta\mathcal{L}^h_{Z\gamma} = \boldsymbol{\kappa_{Z\gamma}}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[t_{\theta_W}A_{\mu\nu}Z^{\mu\nu}+\frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu}+W^+_{\mu\nu}W^{-\mu\nu}\right]$$

$$\Delta\mathcal{L}^h_{GG} = \boldsymbol{\kappa_{GG}}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^A_{\mu\nu}G^{A\,\mu\nu}$$

hVV form-factor correlated with hγZ

$$\Delta\mathcal{L}^h_{ff} = \boldsymbol{\delta g^h_{ff}}\left(h\bar{f}_L f_R+\mathrm{h.c.}\right)\left(1+\frac{3h}{2v}+\frac{h^2}{2v^2}\right)$$

$$\Delta\mathcal{L}_{3h} = \boldsymbol{\delta g_{3h}}\,h^3\left(1+\frac{3h}{2v}+\frac{3h^2}{4v^2}+\frac{h^3}{8v^3}\right)$$

$$\Delta\mathcal{L}^h_{VV} = \boldsymbol{\delta g^h_{VV}}\left[h\left(W^{+\mu}W^-_\mu+\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}\right)+\Delta\right]$$

$$\begin{aligned}\Delta \;=\;& \left(W^{+\mu}W^-_\mu+\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}\right)\left(\frac{2h^2}{v}+\frac{4h^3}{3v^2}+\frac{h^4}{3v^3}\right)+\frac{m_h^2}{12m_W^2}\left(\frac{h^4}{v}+\frac{3h^5}{4v^2}+\frac{h^6}{8v^3}\right)\\ &+\frac{m_f}{4m_W^2}\left(\frac{h^2}{v}+\frac{h^3}{3v^2}\right)\left(\bar{f}_L f_R+\mathrm{h.c.}\right),\end{aligned}$$

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Correlations with triple gauge couplings (TGC):

$$\Delta\mathcal{L}_{\kappa_\gamma} = \frac{\boldsymbol{\delta\kappa_\gamma}}{v^2}\Big[ie\hat{h}^2(A_{\mu\nu} - t_{\theta_W} Z_{\mu\nu})W^{+\mu}W^{-\nu} + Z_\nu\partial_\mu\hat{h}^2(t_{\theta_W}A^{\mu\nu} - t^2_{\theta_W}Z^{\mu\nu})$$
$$+ \frac{(\hat{h}^2 - v^2)}{2}\left(t_{\theta_W}Z_{\mu\nu}A^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right)\Big],$$

$$\hat{h} \equiv v + h$$

hVV form-factor correlated with ZWW

$$\Delta\mathcal{L}_{g_1^Z} = \boldsymbol{\delta g_1^Z}\Bigg[igc_{\theta_W}\left(Z^\mu(W^{+\nu}W^-_{\mu\nu} - \text{h.c.}) + Z^{\mu\nu}W^+_\mu W^-_\nu\right) + \frac{e^2 v}{2c^2_{\theta_W}}hZ_\mu Z^\mu$$
$$- 2c^2_{\theta_W}\frac{h}{v}\left(g(W^-_\mu J^\mu_- + \text{h.c.}) + \frac{gc_{2\theta_W}}{c^3_{\theta_W}}Z_\mu J^\mu_Z + 2et_{\theta_W}Z_\mu J^\mu_{em}\right)\left(1 + \frac{h}{2v}\right)$$
$$- g^2 c^2_{\theta_W}\left(W^+_\mu W^{-\mu} + \frac{c_{2\theta_W}}{2c^4_{\theta_W}}Z_\mu Z^\mu\right)\left(\frac{5}{2}h^2 + 2\frac{h^3}{v} + \frac{h^4}{2v^2}\right) + g^2 c^2_{\theta_W} v\Delta\Bigg].$$

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custodial breaking hVV-coupling
correlated with ZWW

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