# Non-standard Higgs couplings in HAWK

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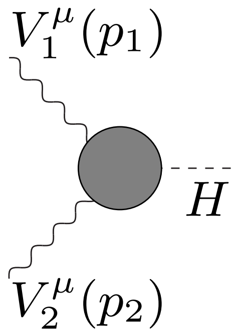
- Implementation in HAWK
- Relation to parametrization of YR3
- Relation to parametrization of Zeppenfeld et al.

# Modified Feynman rules

HAWK: modified $HVV$ couplings (in LO)
modified $HVf\bar{f}$ couplings not (yet) implemented

generalized Feynman rules: $(V_1V_2 = WW, ZZ, Z\gamma, \gamma\gamma)$




$$= \mathrm{i}\, \underbrace{a^{(1)}_{HV_1V_2}}_{\mathrm{SM}} g^{\mu\nu} + \mathrm{i} a^{(2)}_{HV_1V_2} \left[p_1^\nu p_2^\mu - (p_1p_2)g^{\mu\nu}\right] + \mathrm{i} a^{(3)}_{HV_1V_2} \epsilon^{\mu\nu\rho\sigma} p_{1,\rho} p_{2,\sigma}$$

parity-conserving coupling constants: $a^{(1)}_{HV_1V_2}$, $a^{(2)}_{HV_1V_2}$

parity-violating coupling constants: $a^{(3)}_{HV_1V_2}$

Constants $a^{(i)}_{HV_1V_2}$ related to couplings $f_i$ of effective field theory (EFT)

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_k \alpha_k \mathcal{O}_k$$

$\Rightarrow$ must fix a basis of independent dimension-6 effective operators $\mathcal{O}_k$

# HAWK implementation of anomalous couplings

- Philosophy: anomalous couplings (ACs) considered as small corrections to SM predictions
  - QCD corrections dress full AC amplitudes
    (consistent calculation straightforward as ACs are colour blind)
  - EW corrections of SM are added linearly
    terms of order AC$\times$EWRC are neglected
  - take care of sign of $\sin\theta_{\mathrm{w}} = s_{\mathrm{w}}$!
    e.g. $a^{(1)}_{HWW} = \frac{M_{\mathrm{W}}}{s_{\mathrm{w}}} + a^{(1),\mathrm{BSM}}_{HWW}$, convention matters in interference
- optional form factor: (not advocated!)
  $a_{HVV} \to a_{HVV} \times \frac{\Lambda^4}{(\Lambda^2+|k_1|^2)(\Lambda^2+|k_2|^2)}$
  - absent in effective field theory which is only valid for $|k_i^2| \ll \Lambda^2$
  - avoids unitarity violation for $|k_i^2| \sim \Lambda^2$ by ad-hoc prescription
- validation
  - VBF: results validated against VBFNLO
  - WH/ZH: new results from HAWK

# EFT parameterization of YR3

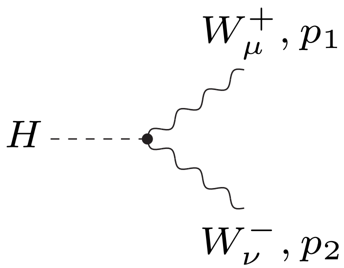
following Grzadkowski et al. ’10

| $\Phi^6$ and $\Phi^4 D^2$ | $\psi^2\Phi^3$ | $X^3$ |
|---|---|---|
| $\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$ | $\mathcal{O}_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_\mathrm{e}\,\mathrm{e}\Phi)$ | $\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ |
| $\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$ | $\mathcal{O}_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_\mathrm{u}\,\mathrm{u}\widetilde{\Phi})$ | $\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ |
| $\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$ | $\mathcal{O}_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_\mathrm{d}\,\mathrm{d}\Phi)$ | $\mathcal{O}_\mathrm{W} = \varepsilon^{IJK} \mathrm{W}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$ |
| | | $\mathcal{O}_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK} \widetilde{\mathrm{W}}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$ |
| $X^2\Phi^2$ | $\psi^2 X\Phi$ | $\psi^2\Phi^2 D$ |
| $\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$ | $\mathcal{O}_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_\mathrm{u}\,\mathrm{u}\widetilde{\Phi}) G_{\mu\nu}^A$ | $\mathcal{O}_{\Phi\mathrm{l}}^{(1)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\mathrm{l})$ |
| $\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi) \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | $\mathcal{O}_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_\mathrm{d}\,\mathrm{d}\Phi) G_{\mu\nu}^A$ | $\mathcal{O}_{\Phi\mathrm{l}}^{(3)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{l}}\gamma^\mu\tau^I\mathrm{l})$ |
| $\mathcal{O}_{\Phi\mathrm{W}} = (\Phi^\dagger\Phi) \mathrm{W}_{\mu\nu}^I \mathrm{W}^{I\mu\nu}$ | $\mathcal{O}_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_\mathrm{e}\,\mathrm{e}\tau^I\Phi) \mathrm{W}_{\mu\nu}^I$ | $\mathcal{O}_{\Phi\mathrm{e}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu\mathrm{e})$ |
| $\mathcal{O}_{\Phi\widetilde{\mathrm{W}}} = (\Phi^\dagger\Phi) \widetilde{\mathrm{W}}_{\mu\nu}^I \mathrm{W}^{I\mu\nu}$ | $\mathcal{O}_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{u}\,\mathrm{u}\tau^I\widetilde{\Phi}) \mathrm{W}_{\mu\nu}^I$ | $\mathcal{O}_{\Phi\mathrm{q}}^{(1)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\mathrm{q})$ |
| $\mathcal{O}_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi) \mathrm{B}_{\mu\nu} \mathrm{B}^{\mu\nu}$ | $\mathcal{O}_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{d}\,\mathrm{d}\tau^I\Phi) \mathrm{W}_{\mu\nu}^I$ | $\mathcal{O}_{\Phi\mathrm{q}}^{(3)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{q}}\gamma^\mu\tau^I\mathrm{q})$ |
| $\mathcal{O}_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi) \widetilde{\mathrm{B}}_{\mu\nu} \mathrm{B}^{\mu\nu}$ | $\mathcal{O}_{\mathrm{eB}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_\mathrm{e}\,\mathrm{e}\Phi) \mathrm{B}_{\mu\nu}$ | $\mathcal{O}_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\mathrm{u})$ |
| $\mathcal{O}_{\Phi\mathrm{WB}} = (\Phi^\dagger\tau^I\Phi) \mathrm{W}_{\mu\nu}^I \mathrm{B}^{\mu\nu}$ | $\mathcal{O}_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{u}\,\mathrm{u}\widetilde{\Phi}) \mathrm{B}_{\mu\nu}$ | $\mathcal{O}_{\Phi\mathrm{d}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu\mathrm{d})$ |
| $\mathcal{O}_{\Phi\widetilde{\mathrm{W}}\mathrm{B}} = (\Phi^\dagger\tau^I\Phi) \widetilde{\mathrm{W}}_{\mu\nu}^I \mathrm{B}^{\mu\nu}$ | $\mathcal{O}_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_\mathrm{d}\,\mathrm{d}\Phi) \mathrm{B}_{\mu\nu}$ | $\mathcal{O}_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_{\mathrm{ud}}\mathrm{d})$ |

+ 25 four-fermion operators

# Feynman rules for HVV vertices (YR3)

$HWW$ coupling: $g = \frac{e}{s_W}$ $\frac{1}{\sqrt{2}G_\mu} = v^2[1 + \mathcal{O}(\alpha_i)]$




$$= \mathrm{i} g M_W g_{\mu\nu} \left[1 + \frac{1}{\sqrt{2}G_\mu\Lambda^2}\left(\alpha_{\phi W} + \alpha_{\phi\Box} - \frac{1}{4}\alpha_{\phi D}\right)\right]$$
$$+ \mathrm{i}\frac{2g}{M_W}\frac{1}{\sqrt{2}G_\mu\Lambda^2}\left[\alpha_{\phi W}(p_{2\mu}p_{1\nu} - p_1p_2 g_{\mu\nu}) + \alpha_{\phi\widetilde{W}}\varepsilon_{\mu\nu\rho\sigma}p_1^\rho p_2^\sigma\right]$$

$$a^{(1)}_{HW^+W^-} = g M_W \left[1 + \frac{1}{\sqrt{2}G_\mu\Lambda^2}\left(\alpha_{\phi W} + \alpha_{\phi\Box} - \frac{1}{4}\alpha_{\phi D}\right)\right]$$

$$a^{(2)}_{HW^+W^-} = \frac{2g}{M_W}\frac{1}{\sqrt{2}G_\mu\Lambda^2}\alpha_{\phi W}, \qquad a^{(3)}_{HW^+W^-} = \frac{2g}{M_W}\frac{1}{\sqrt{2}G_\mu\Lambda^2}\alpha_{\phi\widetilde{W}}$$

$$a^{(1)}_{HZZ} = g\frac{M_Z}{c_W}\left[1 + \frac{1}{\sqrt{2}G_\mu\Lambda^2}\left(\alpha_{\phi W} + \alpha_{\phi\Box} + \frac{1}{4}\alpha_{\phi D}\right)\right]$$

$$a^{(2)}_{HV'V} = \frac{2g}{M_W}\frac{1}{\sqrt{2}G_\mu\Lambda^2}\alpha_{V'V}, \qquad a^{(3)}_{HV'V} = \frac{2g}{M_W}\frac{1}{\sqrt{2}G_\mu\Lambda^2}\alpha_{V'\tilde{V}}, \qquad V'V = ZZ, AZ, AA$$

$$\alpha_{AA} = s_W^2\alpha_{\phi W} + c_W^2\alpha_{\phi B} - c_W s_W \alpha_{\phi WB}$$
$$\alpha_{ZZ} = c_W^2\alpha_{\phi W} + s_W^2\alpha_{\phi B} + c_W s_W \alpha_{\phi WB}$$
$$\alpha_{AZ} = s_W c_W(\alpha_{\phi W} - \alpha_{\phi B}) + \frac{(c_W^2 - s_W^2)}{2}\alpha_{\phi WB}$$

# Input-parameter dependence

Input $M_\mathrm{Z}$, $M_\mathrm{W}$, and $G_\mu$ $\Rightarrow$

$$g = 2M_\mathrm{W}\sqrt{\sqrt{2}G_\mu}\left(1 - \frac{1}{\sqrt{2}G_\mu\Lambda^2}\left(\alpha_{\phi W} + \alpha^{(3)}_{\phi\mu}\right)\right)$$

$\Rightarrow$ $\alpha_{\phi W}$ in rescaled SM coupling replaced by $-\alpha^{(3)}_{\phi\mu}$
(effective operator contributing to $\mu$ decay)

$$a^{(1)}_{HW^+W^-} = gM_\mathrm{W}\left[1 + \frac{1}{\sqrt{2}G_\mu\Lambda^2}\left(\alpha_{\phi W} + \alpha_{\phi\Box} - \frac{1}{4}\alpha_{\phi D}\right)\right]$$

$$\rightarrow \ a^{(1)}_{HW^+W^-} = 2M_\mathrm{W}\sqrt{\sqrt{2}G_\mu}\left[1 + \frac{1}{\sqrt{2}G_\mu\Lambda^2}\left(-\alpha^{(3)}_{\phi\mu} + \alpha_{\phi\Box} - \frac{1}{4}\alpha_{\phi D}\right)\right]$$

expression for $g$ depends on input parameter set and EFT basis!

# Parameterization of Zeppenfeld et al.

Hankele, Klämke, Zeppenfeld, Figy '06 (hep-ph/0609075)
based on Hagiwara, Ishihara, Szalapski, Zeppenfeld '93 (no fermionic operators!)

considered operators: $(\hat{W}_{\mu\nu} = \mathrm{i}g\frac{\sigma^a}{2}W^a_{\mu\nu},\ \hat{B}_{\mu\nu} = \mathrm{i}\frac{g'}{2}B_{\mu\nu},\ \hat{\tilde{V}}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}\hat{V}^{\rho\sigma})$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi, \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$
$$\mathcal{O}_{\tilde{W}W} = \Phi^\dagger \hat{\tilde{W}}_{\mu\nu}\hat{W}^{\mu\nu}\Phi, \qquad \mathcal{O}_{\tilde{B}B} = \Phi^\dagger \hat{\tilde{B}}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

not in basis of Grzadkowski et al. '10

explicit insertions: ($d$ parameters are input to HAWK)

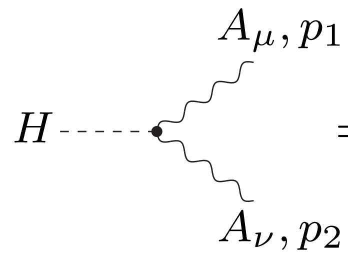
$$a^{(2)}_{HWW} = \frac{2g}{M_\mathrm{W}}d, \qquad a^{(2)}_{HZZ} = \frac{2g}{M_\mathrm{W}}(c^2_\mathrm{w}d + s^2_\mathrm{w}d_B)$$
$$a^{(2)}_{HZ\gamma} = \frac{2g}{M_\mathrm{W}}c_\mathrm{w}s_\mathrm{w}(d - d_B), \qquad a^{(2)}_{H\gamma\gamma} = \frac{2g}{M_\mathrm{W}}(s^2_\mathrm{w}d + c^2_\mathrm{w}d_B)$$
$$a^{(3)}_{HV_1V_2} = a^{(2)}_{HV_1V_2}\Big|_{d\to\tilde{d},\, d_B\to\tilde{d}_B}$$

where

$$d = -\frac{M^2_\mathrm{W}}{\Lambda^2}\alpha_{WW}, \qquad d_B = -\frac{M^2_\mathrm{W}}{\Lambda^2}\frac{s^2_\mathrm{w}}{c^2_\mathrm{w}}\alpha_{BB}$$
$$\tilde{d} = -\frac{M^2_\mathrm{W}}{\Lambda^2}\alpha_{\tilde{W}W}, \qquad \tilde{d}_B = -\frac{M^2_\mathrm{W}}{\Lambda^2}\frac{s^2_\mathrm{w}}{c^2_\mathrm{w}}\alpha_{\tilde{B}B}$$

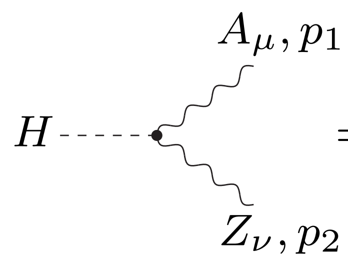
# Feynman rules for Higgs vertices

$HAA$ coupling: $\alpha_{AA} = s_\mathrm{w}^2 \alpha_{\phi W} + c_\mathrm{w}^2 \alpha_{\phi B} - c_\mathrm{w} s_\mathrm{w} \alpha_{\phi WB}$



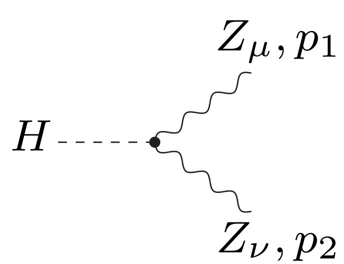

$$= \mathrm{i}\frac{2g}{M_\mathrm{W}} \frac{1}{\sqrt{2} G_\mu \Lambda^2} \left[\alpha_{AA}(p_{2\mu}p_{1\nu} - p_1 p_2 g_{\mu\nu}) + \alpha_{A\tilde{A}} \varepsilon_{\mu\nu\rho\sigma} p_1^\rho p_2^\sigma\right]$$

$HAZ$ coupling: $\alpha_{AZ} = 2 s_\mathrm{w} c_\mathrm{w}(\alpha_{\phi W} - \alpha_{\phi B}) + (c_\mathrm{w}^2 - s_\mathrm{w}^2)\alpha_{\phi WB}$




$$= \mathrm{i}\frac{g}{M_\mathrm{W}} \frac{1}{\sqrt{2} G_\mu \Lambda^2} \left[\alpha_{AZ}(p_{2\mu}p_{1\nu} - p_1 p_2 g_{\mu\nu}) + \alpha_{A\tilde{Z}} \varepsilon_{\mu\nu\rho\sigma} p_1^\rho p_2^\sigma\right]$$

$HZZ$ coupling: $\alpha_{ZZ} = c_\mathrm{w}^2 \alpha_{\phi W} + s_\mathrm{w}^2 \alpha_{\phi B} + c_\mathrm{w} s_\mathrm{w} \alpha_{\phi WB}, \qquad \alpha_{Z\tilde{Z}} = \ldots$




$$= \mathrm{i}g \frac{M_\mathrm{Z}}{c_\mathrm{w}} g_{\mu\nu} \left[1 + \frac{1}{\sqrt{2} G_\mu \Lambda^2} \left(\alpha_{\phi W} + \alpha_{\phi\Box} + \frac{1}{4}\alpha_{\phi D}\right)\right]$$
$$+ \mathrm{i}\frac{2g}{M_\mathrm{W}} \frac{1}{\sqrt{2} G_\mu \Lambda^2} \left[\alpha_{ZZ}(p_{2\mu}p_{1\nu} - p_1 p_2 g_{\mu\nu}) + \alpha_{Z\tilde{Z}} \varepsilon_{\mu\nu\rho\sigma} p_1^\rho p_2^\sigma\right]$$