Effective Lagrangian approach to the EWSB sector

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arXiv:1311.1823
Outline: accessing the EWSB mechanism

- Higgs boson discovery → A particle directly related to the EWSB.
  Its study is an alternative to the direct seek for new resonances.

- Huge variety of data → Higgs analysis, TGV, EWPD...

- Decipher the nature of the EWSB mechanism → deviations, (de)correlations between interactions, special kinematics, new signals
  Studying the Higgs interactions may be the fastest track to understand the origin of EWSB.
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Indirect approach

Model independent parametrization $\rightarrow$ EFFECTIVE LAGRANGIAN APPROACH!
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Outline

Indirect approach

Model independent parametrization → EFFECTIVE LAGRANGIAN APPROACH!

→

Linear: TGV ↔ Higgs physics

Non-linear: decorrelation, alternative signals
Effective Lagrangian: the linear realization

Bottom-up model-independent effective Lagrangian approach:

\[ \mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n \]

- **Particle content**: There is no undiscovered low energy particle. Observed state: scalar, SU(2) doublet, CP-even, narrow and no overlapping resonances.

- **Symmetries**: \( SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \) SM local symmetry (linearly realized). Global symmetries: lepton and baryon number conservation.

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\(^1\) Non-linear CP-odd → arxiv:1406.6367.
Effective Lagrangian for Higgs Interactions

Effective Lagrangian: the linear realization

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59 dimension-6 operators are enough... \hspace{1cm} (Buchmuller et al, Grzadkowski et al)

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- Reduced set considering only C and P even\(^1\).
- EOM to eliminate/choose the basis.
- Huge variety of data to make the choice and reduce the LHC studied set: DATA–DRIVEN.

\(^1\)Non–linear CP–odd → arxiv:1406.6367.
The right of choice

Higgs interactions with gauge bosons:

\[ O_{GG} = \Phi^* \Phi G^a_{\mu\nu} G^{a\mu\nu}, \]
\[ O_{WW} = \Phi^* \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \]
\[ O_{BB} = \Phi^* \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi, \]
\[ O_{\Phi,1} = (D_{\mu} \Phi)^* \Phi^* (D^{\mu} \Phi), \]
\[ O_{\Phi,2} = \frac{1}{2} \partial^\mu (\Phi^* \Phi) \partial_\mu (\Phi^* \Phi), \]
\[ O_{\Phi,4} = (D_{\mu} \Phi)^* (D^{\mu} \Phi) (\Phi^* \Phi), \]

Higgs interactions with fermions:

\[ O_{e\Phi,\mathit{ij}} = (\Phi^* \Phi) (\bar{L}_i \Phi e_{Rj}), \]
\[ O_{u\Phi,\mathit{ij}} = (\Phi^* \Phi) (\bar{Q}_i \Phi u_{Rj}), \]
\[ O_{d\Phi,\mathit{ij}} = (\Phi^* \Phi) (\bar{Q}_i \Phi d_{Rj}), \]
\[ O_{e,\mathit{ij}} = (\Phi^* \Phi) (\bar{e}_{Ri} \gamma^\mu e_{Rj}), \]
\[ O_{u,\mathit{ij}} = (\Phi^* \Phi) (\bar{u}_{Ri} \gamma^\mu u_{Rj}), \]
\[ O_{d,\mathit{ij}} = (\Phi^* \Phi) (\bar{d}_{Ri} \gamma^\mu d_{Rj}), \]
\[ O_{u_d,\mathit{ij}} = \bar{\Phi}^* (iD_{\mu} \Phi) (\bar{u}_{Ri} \gamma^\mu d_{Rj}). \]

In the absence of theoretical prejudice chose a basis where the operators are more directly related to the existing data.
The right of choice

Higgs interactions with gauge bosons:

\[ \mathcal{O}_{GG} = \Phi^\dagger \Phi G^a_{\mu\nu} G^{a\mu\nu}, \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \quad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi, \]
\[ \mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi, \quad \mathcal{O}_{W} = (D_{\mu} \Phi)^\dagger \hat{W}^{\mu\nu} (D_{\nu} \Phi), \quad \mathcal{O}_{B} = (D_{\mu} \Phi)^\dagger \hat{B}^{\mu\nu} (D_{\nu} \Phi), \]
\[ \mathcal{O}_{\Phi,1} = (D_{\mu} \Phi)^\dagger \Phi (D_{\mu} \Phi), \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right), \quad \mathcal{O}_{\Phi,4} = (D_{\mu} \Phi)^\dagger (D_{\mu} \Phi) \left( \Phi^\dagger \Phi \right), \]

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\[ \mathcal{O}_{u\Phi,ij} = (\Phi^\dagger \Phi) (\bar{Q}_i \Phi u_{R_j}), \quad \mathcal{O}_{(1)_{\Phi Q,ij}} = \Phi^\dagger (iD_{\mu} \Phi) (\bar{Q}_i \gamma^\mu Q_j) \]
\[ \mathcal{O}_{d\Phi,ij} = (\Phi^\dagger \Phi) (\bar{Q}_i \Phi d_{R_j}), \quad \mathcal{O}_{(1)_{\Phi e,ij}} = \Phi^\dagger (iD_{\mu} \Phi) (\bar{e}_{R_i} \gamma^\mu e_{R_j}) \]
\[ \mathcal{O}_{(1)_{\Phi u,ij}} = \Phi^\dagger (iD_{\mu} \Phi) (\bar{u}_{R_i} \gamma^\mu u_{R_j}) \]
\[ \mathcal{O}_{(1)_{\Phi d,ij}} = \Phi^\dagger (iD_{\mu} \Phi) (\bar{d}_{R_i} \gamma^\mu d_{R_j}) \]
\[ \mathcal{O}_{(1)_{\Phi u d,ij}} = \Phi^\dagger (iD_{\mu} \Phi) (\bar{u}_{R_i} \gamma^\mu d_{R_j}) \]

In the absence of theoretical prejudice chose a basis where the operators are more directly related to the existing data:

\[ 2 D_{\mu} \Phi = \left( \partial_{\mu} + i \frac{1}{2} g' B_{\mu} + ig \frac{\sigma^a}{2} W^a_{\mu} \right) \Phi, \quad \hat{B}_{\mu\nu} = i \frac{g'}{2} B_{\mu\nu}, \quad \hat{W}_{\mu\nu} = i \frac{g}{2} \sigma^a W^a_{\mu\nu}. \]
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\[ O_{WW} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi), \]
\[ O_{B_B} = (D_\mu \Phi)^\dagger (D_\mu \Phi) \left( \Phi^\dagger \Phi \right), \]
\[ O_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D_\mu \Phi), \]
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\[ O_{e,ij} = (\Phi^\dagger \Phi) (\bar{e}_R i \gamma^\mu e_R j) \]
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\[ O_{d,ij} = (\Phi^\dagger \Phi) (\bar{d}_R i \gamma^\mu d_R j) \]
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In the absence of theoretical prejudice chose a basis where the operators are more directly related to the existing data.

\[ 2 D_\mu \Phi = \left( \partial_\mu + i \frac{1}{2} g' B_\mu + i g \frac{\sigma^a}{2} W^a_\mu \right) \Phi, \]
\[ \hat{B}_{\mu\nu} = \frac{g'}{2} B_{\mu\nu}, \]
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Higgs interactions with gauge bosons:\(^2\):

\[ O_{GG} = \Phi^\dagger \Phi G_\mu^a G^{a\mu
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\[ 2D_\mu \Phi = \left( \partial_\mu + \frac{i\gamma^5}{2} g' B_\mu + ig \frac{\sigma_5}{2} W_\mu^a \right) \Phi, \hat{B}_\mu = \frac{g'}{2} B_\mu, \hat{W}_\mu = \frac{g}{2} \sigma_5 W_\mu^a \]
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\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi^\dagger (D^\mu \Phi) , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right) , \quad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger (D^\mu \Phi) \left( \Phi^\dagger \Phi \right) ,
\]

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\[
\mathcal{O}_{e\Phi,i,j} = (\Phi^\dagger \Phi)(\bar{L}_i \Phi e_{Rj}) \quad \mathcal{O}_{eL,i,j} = \Phi^\dagger (iD_\mu \Phi)(\bar{L}_i \gamma^\mu L_j) \quad \mathcal{O}_{eL,ij} = \Phi^\dagger (iD^a_\mu \Phi)(\bar{L}_i \gamma^\mu \sigma_a L_j)
\]
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\]
\[
\mathcal{O}_{d\Phi,i,j} = (\Phi^\dagger \Phi)(\bar{Q}_i \Phi d_{Rj}) \quad \mathcal{O}_{dL,i,j} = \Phi^\dagger (iD_\mu \Phi)(\bar{e}_{Ri} \gamma^\mu e_{Rj}) \quad \mathcal{O}_{dL,ij} = \Phi^\dagger (iD^a_\mu \Phi)(\bar{\bar{e}}_{Ri} \gamma^\mu \sigma_a e_{Rj})
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\]
\[
\mathcal{O}_{udL,i,j} = \tilde{\Phi}^\dagger (iD^a_\mu \Phi)(\bar{\bar{u}}_{Ri} \gamma^\mu d_{Rj})
\]

In the absence of theoretical prejudice chose a basis where the operators are more directly related to the existing data

\[
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In the absence of theoretical prejudice chose a basis where the operators are more directly related to the existing data TGV,
The right of choice

Higgs interactions with gauge bosons:

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\[ O_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi , \quad O_W = (D_{\mu} \Phi)^\dagger \hat{W}^{\mu\nu} (D_{\nu} \Phi) , \quad O_B = (D_{\mu} \Phi)^\dagger \hat{B}^{\mu\nu} (D_{\nu} \Phi) , \]

\[ O_{\Phi,1} = (D_{\mu} \Phi)^\dagger \Phi (D_{\mu} \Phi) , \quad O_{\Phi,2} = \frac{1}{2} \partial_{\mu} \left( \Phi^\dagger \Phi \right) \partial_{\mu} \left( \Phi^\dagger \Phi \right) , \quad O_{\Phi,4} = (D_{\mu} \Phi)^\dagger (D_{\mu} \Phi) \left( \Phi^\dagger \Phi \right) , \]

Higgs interactions with fermions:

\[ O_{e\Phi,i,j} = (\Phi^\dagger \Phi)(\bar{L}_i \Phi e_{R_j}) \quad (1) \quad \Phi_L,i_j = \Phi^\dagger (iD_{\mu} \Phi)(\bar{L}_i \gamma^\mu L_j) \quad (3) \quad \Phi_Q,i_j = \Phi^\dagger (iD_{\mu} \Phi)(\bar{Q}_i \gamma^\mu Q_j) \]

\[ O_{u\Phi,i,j} = (\Phi^\dagger \Phi)(\bar{Q}_i \Phi u_{R_j}) \quad (1) \quad \Phi_Q,i_j = \Phi^\dagger (iD_{\mu} \Phi)(\bar{Q}_i \gamma^\mu Q_j) \]

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TGV, Z properties, W decays, low energy ν scattering, atomic P, FCNC, Moller scattering P and e^+ e^- → f f at LEP2 and tree level contribution to the oblique parameters: must avoid blind directions.
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\[ O_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi , \]
\[ O_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi , \]
\[ O_{W} = (D_{\mu} \Phi)^\dagger \hat{W}_{\mu\nu} (D_{\nu} \Phi) , \]
\[ O_{B} = (D_{\mu} \Phi)^\dagger \hat{B}_{\mu\nu} (D_{\nu} \Phi) , \]
\[ O_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_{\mu} \left( \Phi^\dagger \Phi \right) , \]

Higgs interactions with fermions:

\[ O_{e\Phi,33} = (\Phi^\dagger \Phi) (\bar{L}_3 \Phi e_{R3}) \]
\[ O_{d\Phi,33} = (\Phi^\dagger \Phi) (\bar{Q}_3 \Phi d_{R3}) \]

In the absence of theoretical prejudice chose a basis where the operators are more directly related to the existing data

TGV, Z properties, W decays, low energy \( \nu \) scattering, atomic P, FCNC, Moller scattering \( P \) and \( e^+ e^- \rightarrow f \bar{f} \) at LEP2 and
tree level contribution to the oblique parameters: must avoid blind directions.
Effective Lagrangian for Higgs Interactions

\[ \mathcal{L}_{\text{eff}} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_{B}}{\Lambda^2} \mathcal{O}_{B} + \frac{f_{W}}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\tau}}{\Lambda^2} \mathcal{O}_{e\Phi,33} + \frac{f_{\text{bot}}}{\Lambda^2} \mathcal{O}_{d\Phi,33} \]

Unitary gauge:

\[ \mathcal{L}_{\text{eff}}^{HVV} = g_{Hgg} H G_{\mu \nu}^{a} G^{a \mu \nu} + g_{H \gamma \gamma} H A_{\mu \nu} A^{\mu \nu} + g_{H}^{(1)} H Z_{\gamma} \gamma A_{\mu \nu} Z^{\mu} \partial^{\nu} H + g_{H}^{(2)} H Z_{\gamma} \gamma H A_{\mu \nu} Z^{\mu \nu} \]
\[ + g_{H}^{(1)} H Z_{\mu \nu} Z^{\mu} \partial^{\nu} H + g_{H}^{(2)} H Z_{\mu \nu} Z^{\mu \nu} + g_{H}^{(3)} H Z_{\mu} Z^{\mu} \]
\[ + g_{H}^{(1)} H W W \left( W^{+}_{\mu \nu} W^{- \mu} \partial^{\nu} H + \text{h.c.} \right) + g_{H}^{(2)} H W W \left( W^{+}_{\mu \nu} W^{- \mu \nu} + g_{H}^{(3)} H W W \right) W_{\mu}^{+} W^{- \mu} \]

\[ \mathcal{L}_{\text{eff}}^{Hff} = g_{H}^{f} f_{L}^{f'} f_{R}^{'} H + \text{h.c.} \]

\[ g_{Hgg} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2}, \quad g_{H \gamma \gamma} = - \left( \frac{g^2 v s^2}{2\Lambda^2} \right) \frac{f_{WW} + f_{BB}}{2}, \]

\[ g_{H}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s(f_{WW} - f_{BB})}{2c}, \quad g_{H}^{(2)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c}, \]

\[ g_{H}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{c^2 f_{WW} + s^2 f_{BB}}{2c^2}, \quad g_{H}^{(2)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2}, \]

\[ g_{H}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_{WW}}{2}, \quad g_{H}^{(2)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_{WW}}{2} \]

\[ g_{H}^{f} = - \frac{m_{i}^{f}}{v} \delta_{ij} + \frac{v^2}{\sqrt{2\Lambda^2}} f'_{\Phi,ij}, \quad g_{\Phi}^{2} = g_{H}^{SM} \left( 1 - \frac{v^2}{2\Lambda^2} \right) \]

Juan González Fraile (UB) | Johns Hopkins 2014 | Heidelberg, July 2014 | 5 / 23
Effective Lagrangian for Higgs Interactions

\[ L_{\text{eff}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} O_{GG} + \frac{f_{\Phi,2}}{\Lambda^2} O_{\Phi,2} + \frac{f_{BB}}{\Lambda^2} O_{BB} + \frac{f_{WW}}{\Lambda^2} O_{WW} + \frac{f_B}{\Lambda^2} O_B + \frac{f_W}{\Lambda^2} O_W + \frac{f_\tau}{\Lambda^2} O_{\Phi,33} + \frac{f_{\text{bot}}}{\Lambda^2} O_{d,33} \]

Unitary gauge:

\[ L_{\text{eff}}^{HVV} = g_{Hgg} H G_{\mu\nu}^{a} G^{a\mu\nu} + g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{H Z Z}^{(1)} H Z_{\mu\nu} Z^{\mu\nu} + g_{H Z Z}^{(2)} H Z_{\mu\nu} Z^{\mu\nu} + g_{H Z Z}^{(3)} H Z_{\mu} Z_{\mu} \]

\[ L_{\text{eff}}^{H_{ij}f} = g_{H_{ij}}^{f} f_{L} f_{R} H + \text{h.c.} \]

\[ g_{Hgg} = -\frac{\alpha_s f_g v}{8\pi \Lambda^2}, \quad g_{H\gamma\gamma} = - \left( \frac{g^2 v s^2}{2\Lambda^2} \right) \frac{f_{WW} + f_{BB}}{2}, \]

\[ g_{H Z Z}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s(f_W - f_B)}{2c}, \quad g_{H Z Z}^{(2)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c}, \]

\[ g_{H Z Z}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{c^2 f_W + s^2 f_B}{2c^2}, \quad g_{H Z Z}^{(2)} = - \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2}, \]

\[ g_{H W W}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_W}{2}, \quad g_{H W W}^{(2)} = - \left( \frac{g^2 v}{2\Lambda^2} \right) f_{WW}, \]

\[ g_{H_{ij}}^{f} = -\frac{m_{i}^{f}}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} f_{f_{i}j}^{f}, \quad g_{\Phi,2}^{H_{xx}} = g_{H_{xx}}^{SM} \left( 1 - \frac{v^2}{2} \frac{f_{\Phi,2}}{\Lambda^2} \right). \]
Effective Lagrangian for Higgs Interactions

\[ \mathcal{L}_{\text{eff}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_{B}}{\Lambda^2} \mathcal{O}_{B} + \frac{f_{W}}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\tau}}{\Lambda^2} \mathcal{O}_{e\Phi,33} + \frac{f_{\text{bot}}}{\Lambda^2} \mathcal{O}_{d\Phi,33} \]

Unitary gauge:

\[ \mathcal{L}^{HVV}_{\text{eff}} = g_{Hgg} H G_{\mu\nu}^a G^{a\mu\nu} + g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{HZZ}^{(1)} A_{\mu\nu} Z^\mu \partial^\nu H + g_{HZZ}^{(2)} A_{\mu\nu} Z^\mu + g_{HZZ}^{(3)} H Z_{\mu\nu} Z^\mu \]

\[ + \ g_{HWW}^{(1)} (W_{\mu\nu}^+ W_{-\mu} H + \text{h.c.}) + g_{HWW}^{(2)} H W_{-\mu} W_{\mu} + g_{HWW}^{(3)} H W_{\mu} W_{\mu} \]

\[ \mathcal{L}^{Hff}_{\text{eff}} = g_{Hij}^f \bar{f}_L^f f_R^j H + \text{h.c.} \]

\[ g_{Hgg} = -\frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} \quad , \quad g_{H\gamma\gamma} = -\left( \frac{g^2 v s^2}{2\Lambda^2} \right) \frac{f_{WW} + f_{BB}}{2} \]

\[ g_{HZZ}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s (f_W - f_B)}{2c} \quad , \quad g_{HZZ}^{(2)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{2s^2 f_{BB} - 2c^2 f_{WW}}{2c} \]

\[ g_{HZZ}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{c^2 f_W + s^2 f_B}{2c^2} \quad , \quad g_{HZZ}^{(2)} = -\left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \]

\[ g_{HWW}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_W}{2} \quad , \quad g_{HWW}^{(2)} = -\left( \frac{g^2 v}{2\Lambda^2} \right) f_{WW} \]

\[ g_{Hij}^f = -\frac{m_i^f}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} f_{f^f,i}^f \quad , \quad g_{Hxx}^{(1)} = g_{Hxx}^{SM} (1 - \nu^2 \frac{f_{\Phi,2}}{2\Lambda^2}) \]
Effective Lagrangian for Higgs Interactions

\[ \mathcal{L}_{\text{eff}} = -\frac{\alpha_s v}{8\pi} \frac{g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\tau}}{\Lambda^2} \mathcal{O}_{\Phi,33} + \frac{f_{\text{bot}}}{\Lambda^2} \mathcal{O}_{d\Phi,33} \]

Unitary gauge:

\[ \mathcal{L}_{\text{eff}}^{HVV} = \mathcal{O}_{HVV} \]

\[ \mathcal{L}_{\text{eff}}^{Hff} = \mathcal{O}_{Hff} \]

Unitary gauge:

\[ g_{Hgg} = -\frac{\alpha_s f g v}{8\pi} \frac{g}{\Lambda^2} \]

\[ g_{Hg}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s(fW - f_B)}{2c} \]

\[ g_{Hg}^{(2)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \]

\[ g_{HZZ}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{c^2 f_W + s^2 f_B}{2c^2} \]

\[ g_{HZZ}^{(2)} = -\left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \]

\[ g_{HWW}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_W}{2} \]

\[ g_{HWW}^{(2)} = -\left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_{WW}}{2} \]

\[ g_{Hi}^{f} = -\frac{m_i^f}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} f'_{
u,ij} \]

\[ g_{\Phi,2} = g_{\Phi,2}^{SM} \left( 1 - \frac{v^2}{2\Lambda^2} f_{\Phi,2} \right) \]
Effective Lagrangian for Higgs Interactions

\[ \mathcal{L}_{\text{eff}} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_\tau}{\Lambda^2} \mathcal{O}_{e\Phi,33} + \frac{f_{\text{bot}}}{\Lambda^2} \mathcal{O}_{d\Phi,33} \]

Unitary gauge:

\[ \mathcal{L}_{\text{HVV}}^\text{HVV} = g_{Hgg} H G_{\mu\nu}^a G^{a\mu\nu} + g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{H Z \gamma}^{(1)} A_{\mu\nu} Z^\mu \partial^\nu H + g_{H Z \gamma}^{(2)} H A_{\mu\nu} Z^\mu + g_{H Z \gamma}^{(3)} H Z_{\mu\nu} Z^{\mu\nu} + g_{H Z \gamma}^{(4)} H Z_{\mu\nu} H Z^{\mu\nu} \]

\[ \mathcal{L}_{\text{Hff}}^\text{Hff} = g_{H\Phi,ij}^f f_L^i f_R^j H + \text{h.c.} \]

\[ g_{Hgg} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \]

\[ g_{H\gamma\gamma} = - \left( \frac{g^2 v s^2}{2\Lambda^2} \right) \frac{f_{WW} + f_{BB}}{2} \]

\[ g_{H Z \gamma}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s(f_W - f_B)}{2c} \]

\[ g_{H Z \gamma}^{(2)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \]

\[ g_{H Z \gamma}^{(3)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{c^2 f_W + s^2 f_B}{2c^2} \]

\[ g_{H Z \gamma}^{(4)} = - \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \]

\[ g_{HWW}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_W}{2} \]

\[ g_{HWW}^{(2)} = - \left( \frac{g^2 v}{2\Lambda^2} \right) f_{WW} \]

\[ g_{H\Phi,ij}^f = - \frac{m_f^i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2} \Lambda^2} f'_{\Phi,ij} \]

\[ g_{\Phi,2} = g_{H\Phi,2}^\text{SM} \left( 1 - \frac{v^2}{2} \frac{f_{\Phi,2}}{\Lambda^2} \right) \]
Effective Lagrangian for Higgs Interactions

\[
\mathcal{L}_{\text{eff}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_G + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_\tau}{\Lambda^2} \mathcal{O}_{e\Phi,33} + \frac{f_{\text{bot}}}{\Lambda^2} \mathcal{O}_{d\Phi,33}
\]

Unitary gauge:

\[
\mathcal{L}_{\text{eff}}^{HVV} = g_{Hgg} H G_{\mu\nu}^a G^{a\mu\nu} + g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{HZZ}^1 H Z_{\mu\nu} Z^{\mu\nu} + g_{HZZ}^2 H Z_{\mu\nu} Z^{\mu\nu} + g_{HZZ}^3 H Z_{\mu} Z_{\mu} + \text{h.c.}
\]

\[
\mathcal{L}_{\text{eff}}^{Hff} = g_{Hij}^f \bar{f}_L \gamma_5 f_R H + \text{h.c.}
\]

\[
g_{Hgg} = -\frac{\alpha_s f_g v}{8\pi} \frac{f_g}{\Lambda^2}, \quad g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right) \frac{f_{WW}}{2} + \frac{f_{BB}}{2}
\]

\[
g_{HZZ}^1 = \left(\frac{g^2 v}{2\Lambda^2}\right) \left(\frac{s f_W - f_B}{2c}\right), \quad g_{HZZ}^2 = \left(\frac{g^2 v}{2\Lambda^2}\right) \left[\frac{s^2 f_{BB} - 2c^2 f_{WW}}{2c}\right],
\]

\[
g_{HWW}^1 = \left(\frac{g^2 v}{2\Lambda^2}\right) \left(\frac{f_W}{2}\right), \quad g_{HWW}^2 = -\left(\frac{g^2 v}{2\Lambda^2}\right) \frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2},
\]

\[
g_{Hij}^f = -\frac{m_i}{v} \delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} f_{\Phi,i}^f, \quad g_{Hxx}^\Phi = g_{Hxx}^{SM} \left(1 - \frac{v^2}{2\Lambda^2}\right),
\]
Higgs collider data

\[ \chi^2 = \min_{\xi_{\text{pull}}} \sum_j \frac{(\mu_j - \mu_{j,\text{exp}})^2}{\sigma_j^2} + \sum_{\text{pull}} \left( \frac{\xi_{\text{pull}}}{\sigma_{\text{pull}}} \right)^2 \]

Where

\[ \mu_F = \frac{\epsilon^F_{gg} \sigma_{gg}^{\text{ano}} + \epsilon^F_{VBF} \sigma_{VBF}^{\text{ano}} + \epsilon^F_{WH} \sigma_{WH}^{\text{ano}} + \epsilon^F_{ZH} \sigma_{ZH}^{\text{ano}} + \epsilon^F_{t\bar{t}H} \sigma_{t\bar{t}H}^{\text{ano}}}{\epsilon^F_{gg} \sigma_{gg}^{\text{SM}} + \epsilon^F_{VBF} \sigma_{VBF}^{\text{SM}} + \epsilon^F_{WH} \sigma_{WH}^{\text{SM}} + \epsilon^F_{ZH} \sigma_{ZH}^{\text{SM}} + \epsilon^F_{t\bar{t}H} \sigma_{t\bar{t}H}^{\text{SM}}} \otimes \frac{\text{BR}^{\text{ano}}[h \to F]}{\text{BR}^{\text{SM}}[h \to F]} \]

where \( \sigma_x^{\text{ano}} = \sigma_x^{\text{ano}}(1 + \xi_x) \).

For the anomalous calculations:

\[ \sigma_Y^{\text{ano}} = \frac{\sigma_Y^{\text{ano}}}{\sigma_Y^{\text{SM}}} \bigg|_{\text{tree}} \sigma_Y^{\text{SM}} \bigg|_{\text{soa}} \]

and

\[ \Gamma^{\text{ano}}(h \to X) = \frac{\Gamma^{\text{ano}}(h \to X)}{\Gamma^{\text{SM}}(h \to X)} \bigg|_{\text{tree}} \Gamma^{\text{SM}}(h \to X) \bigg|_{\text{soa}} \]
Analysis Framework

Higgs collider data

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Johns Hopkins 2014

Heidelberg, July 2014 7 / 23
TGV and EWPD

**TGV:**
\[
\mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V \left( W_{\mu \nu}^+ W_{- \mu}^\nu - W_{\mu}^+ V_{\nu} W_{- \mu}^\nu \right) + \kappa V W_{\mu}^+ W_{- \nu}^\nu + \frac{\lambda V m_{WW}}{\Lambda^2} W_{\mu \nu}^+ W_{- \nu}^\mu \right\}
\]

\[
\Delta g_1^Z = g_1^Z - 1 = \frac{g^2 v^2}{8 c^2 \Lambda^2} f_W,
\]

\[
\Delta \kappa_\gamma = \kappa_\gamma - 1 = \frac{g^2 v^2}{8 \Lambda^2} (f_W + f_B), \quad \leftrightarrow \quad g_1^Z = 0.984^{+0.049}_{-0.049} \quad \text{LEP}
\]

\[
\Delta \kappa_Z = \kappa_Z - 1 = \frac{g^2 v^2}{8 c^2 \Lambda^2} (c^2 f_W - s^2 f_B).
\]

**EWPD:**

\[
\Delta S = 0.00 \pm 0.10 \quad \Delta T = 0.02 \pm 0.11 \quad \Delta U = 0.03 \pm 0.09
\]

\[
\rho = \begin{pmatrix}
1 & 0.89 & -0.55 \\
0.89 & 1 & -0.8 \\
-0.55 & -0.8 & 1
\end{pmatrix}
\]

\(O_{BW}\) and \(O_{\Phi,1}\) can already be neglected for the LHC analysis:

\[
\alpha \Delta S = e^2 \frac{v^2}{\Lambda^2} f_{BW} \quad \text{and} \quad \alpha \Delta T = \frac{1}{2} \frac{v^2}{\Lambda^2} f_{\Phi,1}.
\]

We add the rest of one-loop contributions in parts of the analysis.
\[
\alpha \Delta S - \frac{1}{6} \frac{e^2}{16\pi^2} \left\{ 3(f_W + f_B) \frac{m_H^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_H^2} \right) + \\
+ 2 \left[ (5c^2 - 2)f_W - (5c^2 - 3)f_B \right] \frac{m_Z^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) \\
- \left[ (22c^2 - 1)f_W - (30c^2 + 1)f_B \right] \frac{m_Z^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) \\
- 24c^2 f_W W \frac{m_Z^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) + 2 f_{\Phi,2} \frac{v^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) \right\},
\]

\[
\alpha \Delta T = \frac{3}{4c^2} \frac{e^2}{16\pi^2} \left\{ f_B \frac{m_H^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_H^2} \right) \\
+ (c^2 f_W + f_B) \frac{m_Z^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) \\
+ \left[ 2c^2 f_W + (3c^2 - 1)f_B \right] \frac{m_Z^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) - f_{\Phi,2} \frac{v^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) \right\},
\]

\[
\alpha \Delta U = -\frac{1}{3} \frac{e^2 s^2}{16\pi^2} \left\{ (-4f_W + 5f_B) \frac{m_Z^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) \\
+ (2f_W - 5f_B) \frac{m_Z^2}{\Lambda^2} \log \left( \frac{\Lambda^2}{m_Z^2} \right) \right\}
\]
$\Delta \chi^2$ vrs $f_X$
$\Delta \chi^2 \text{ vrs } f_X$
$\Delta \chi^2$ vrs $f_X$
2d correlations

Fit with $f_g, f_{WW} = -f_{BB}, f_W, f_B, f_{42}, f_{40}$, $f_z = 0$
Present Status

BRs and production CS

\[ \Delta \chi^2 \]

\[ \frac{f_{\text{bot}} 
eq 0}{f_{\tau} 
eq 0} \]

\[ \frac{\text{BR}^{\text{ano}}}{\text{BR}^{\text{SM}}} \]

\[ \frac{\sigma^{\text{ano}}}{\sigma^{\text{SM}}} \]

Graph showing \( \Delta \chi^2 \) for different processes with significance levels for 68%, 90%, and 95%.
Gauge Invariance → TGV and Higgs couplings related: $\mathcal{O}_W$ and $\mathcal{O}_B$

**Complementarity in experimental searches:** Higgs data bounds on

$$f_W \otimes f_B \equiv \Delta \kappa_\gamma \otimes \Delta g_1^Z$$

$$\Delta g_1^Z = g_1^Z - 1 = \frac{g^2 v^2}{8 c^2 \Lambda^2} f_W,$$

$$\Delta \kappa_\gamma = \kappa_\gamma - 1 = \frac{g^2 v^2}{8 \Lambda^2} (f_W + f_B),$$

$$\Delta \kappa_Z = \kappa_Z - 1 = \frac{g^2 v^2}{8 c^2 \Lambda^2} (c^2 f_W - s^2 f_B).$$
Determining TGV from Higgs data

Correlation between TGV and Higgs signals

\[ \mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V (W_{\mu\nu}^+ W_{-\mu\nu}^- + \kappa_V W_{\mu\nu}^+ W_{-\mu\nu}^- V_{\mu\nu}) \right\} \]

\[ \Delta g_1^Z = \frac{g^2 v^2}{8c^2 \Lambda^2} f_W, \]

\[ \Delta \kappa_\gamma = \frac{g^2 v^2}{8\Lambda^2} (f_W + f_B), \]

\[ \Delta \kappa_Z = \frac{g^2 v^2}{8c^2 \Lambda^2} (c^2 f_W - s^2 f_B). \]

\[ \mathcal{L}_{\text{eff}}^{HWW} = +g_{HWW}^{(1)} (W_{\mu\nu}^+ W_{-\mu\nu}^- \partial^\nu H + \text{h.c.}) + g_{HWW}^{(2)} H W_{\mu\nu}^+ W_{-\mu\nu}^- + g_{HWW}^{(3)} H W_{\mu\nu}^+ W_{-\mu\nu}^- \]

\[ g_{HWW}^{(1)} = \left( \frac{g^2 v}{2\Lambda^2} \right) \frac{f_W}{2}, \]

\[ g_{HWW}^{(2)} = -\left( \frac{g^2 v}{2\Lambda^2} \right) f_{WW}, \]

\[ g_{HWW}^{(3)} = g_{HWW}^{SM} \left( 1 - \frac{v^2}{2} \frac{f_{\Phi,2}}{\Lambda^2} \right). \]

Assume: LHC see deviation to TGV within 95% CL bound verifying \( \Delta \kappa_\gamma = \Delta \kappa_Z = \cos^2 \theta_W \Delta g_1^Z \)

e. g. \[ \frac{f_W}{\Lambda^2} = -6.5 \text{ TeV}^{-2} \]

Leading to the excess

\[ \sigma(pp \to WH) = 1.65\sigma_{SM}(pp \to WH) \]

\[ \Rightarrow \text{but with a distorted } H p_T \text{ spectrum!} \]
Motivated by composite models → Higgs as a PGB of a global symmetry.

Non-linear or “chiral“ effective Lagrangian expansion including the light Higgs.

\[ F_i(h) = 1 + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \ldots \]

Light Higgs → without a given model treated as generic "singlet" \( h \)

\( h \) is not part of \( \Phi \)

More possible operators

Dimensionless unitary matrix: \( U(x) = e^{i\sigma a \pi^a(x)/v} \)

Relative reshuffling of the order at which operators appear

Bosonic (pure gauge and gauge-\( h \) operators) and Yukawa-like up to four derivatives

\[ \mathcal{L}_{\text{chiral}} = \mathcal{L}_0 + \Delta \mathcal{L} \]

Comparison with the linear basis!
The Non-linear Lagrangian

\[ \mathcal{L}_{\text{chiral}} = \mathcal{L}_0 + \Delta \mathcal{L} \]

SM Lagrangian\(^3\)

\[ \mathcal{L}_0 = \frac{1}{2} (\partial_\mu h)(\partial^\mu h) - \frac{1}{4} W^a_\mu W^{a\mu} - \frac{1}{4} B_\mu B^{\mu} - \frac{1}{4} G^a_\mu G^{a\mu} - V(h) \]

\[ -\frac{(v + h)^2}{4} \text{Tr}[V_\mu V^\mu] + i\bar{Q}PQ + i\bar{L}PL \]

\[ -\frac{v + s_Y h}{\sqrt{2}} (\bar{Q}L U Y_Q Q_R + \text{h.c.}) - \frac{v + s_Y h}{\sqrt{2}} (\bar{L}_L U Y_L L_R + \text{h.c.}) \]

Restricting to bosonic (pure gauge and gauge-\(h\) operators):

\[ \Delta \mathcal{L} = \xi [c_B \mathcal{P}_B(h) + c_W \mathcal{P}_W(h) + c_G \mathcal{P}_G(h) + c_C \mathcal{P}_C(h) + c_T \mathcal{P}_T(h) \]

\[ + c_H \mathcal{P}_H(h) + c_{\Box}H \mathcal{P}_{\Box}H(h)] + \xi \sum_{i=1}^{10} c_i \mathcal{P}_i(h) \]

\[ + \xi^2 \sum_{i=11}^{25} c_i \mathcal{P}_i(h) + \xi^4 c_{26} \mathcal{P}_{26}(h) + \sum_i \xi^{n_i} c^i_{HH} \mathcal{P}^i_{HH}(h) \]

\(^3\) \(D_\mu U(x) \equiv \partial_\mu U(x) + ig W_\mu(x) U(x) - \frac{ig'}{2} B_\mu(x) U(x) \sigma_3 \)

\(Y_Q \equiv \text{diag}(Y_U, Y_D)\), \quad \(Y_L \equiv \text{diag}(Y_\nu, Y_L)\).
Disentangling a dynamical Higgs

The Non-linear Lagrangian

\[ \mathcal{P}_C(h) = -\frac{v^2}{4} \text{Tr}(V^\mu V_\mu) \mathcal{F}_C(h) \]

\[ \mathcal{P}_T(h) = \frac{v^2}{4} \text{Tr}(TV_\mu) \text{Tr}(TV^\mu) \mathcal{F}_T(h) \]

\[ \mathcal{P}_H(h) = \frac{1}{2} (\partial_\mu h)(\partial^\mu h) \mathcal{F}_H(h) \]

\[ \mathcal{P}_B(h) = -\frac{g^2}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h) \]

\[ \mathcal{P}_W(h) = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h) \]

\[ \mathcal{P}_G(h) = -\frac{g^2}{4} G^a_{\mu\nu} G^{a\mu\nu} \mathcal{F}_G(h) \]

\[ \mathcal{P}_1(h) = g g' B_{\mu\nu} \text{Tr}(TW^{\mu\nu}) \mathcal{F}_1(h) \]

\[ \mathcal{P}_2(h) = ig' B_{\mu\nu} \text{Tr}(T[V^\mu, V^\nu]) \mathcal{F}_2(h) \]

\[ \mathcal{P}_3(h) = ig \text{Tr}(W_{\mu\nu}[V^\mu, V^\nu]) \mathcal{F}_3(h) \]

\[ \mathcal{P}_4(h) = ig' B_{\mu\nu} \text{Tr}(TV^\mu) \partial^\nu \mathcal{F}_4(h) \]

\[ \mathcal{P}_5(h) = ig \text{Tr}(W_{\mu\nu} V^\mu) \partial^\nu \mathcal{F}_5(h) \]

\[ \mathcal{P}_6(h) = (\text{Tr}(V^\mu V_\mu))^2 \mathcal{F}_6(h) \]

\[ \mathcal{P}_7(h) = \text{Tr}(V^\mu V_\mu) \partial_\nu \partial^\nu \mathcal{F}_7(h) \]

\[ \mathcal{P}_8(h) = \text{Tr}(V^\mu V_\nu) \partial^\mu \mathcal{F}_8(h) \partial^\nu \mathcal{F}'_8(h) \]

\[ \mathcal{P}_9(h) = \text{Tr}((D_\mu V^\mu)^2) \mathcal{F}_9(h) \]

\[ \mathcal{P}_{10}(h) = \text{Tr}(V_\nu D_\mu V^\mu) \partial^\nu \mathcal{F}_{10}(h) \]

\[ \mathcal{P}_{\Box H} = \frac{1}{v^2} (\partial_\mu \partial^\mu h)^2 \mathcal{F}_{\Box H}(h) \]
The Non-linear Lagrangian

\[ \mathcal{P}_C(h) = -\frac{v^2}{4} \text{Tr}(V^\mu V_\mu)F_C(h) \]

\[ \mathcal{P}_T(h) = \frac{v^2}{4} \text{Tr}(TV^\mu)\text{Tr}(TV^\nu)F_T(h) \]

\[ \mathcal{P}_H(h) = \frac{1}{2} (\partial_\mu h)(\partial^\mu h)F_H(h) \]

\[ \mathcal{P}_B(h) = -\frac{g^2}{4} B_{\mu\nu}B^{\mu\nu}F_B(h) \]

\[ \mathcal{P}_W(h) = -\frac{g^2}{4} W^a_{\mu\nu} W^{a\mu\nu}F_W(h) \]

\[ \mathcal{P}_G(h) = -\frac{g^2}{4} G^a_{\mu\nu}G^{a\mu\nu}F_G(h) \]

\[ \mathcal{P}_1(h) = gg' B_{\mu\nu} \text{Tr}(TW^{\mu\nu})F_1(h) \]

\[ \mathcal{P}_2(h) = ig' B_{\mu\nu} \text{Tr}(T[V^\mu, V^\nu])F_2(h) \]

\[ \mathcal{P}_3(h) = ig \text{Tr}(W_{\mu\nu}[V^\mu, V^\nu])F_3(h) \]

\[ \mathcal{P}_4(h) = ig' B_{\mu\nu} \text{Tr}(TV^\mu)\partial^\nu F_4(h) \]

\[ \mathcal{P}_5(h) = ig \text{Tr}(W_{\mu\nu}V^\mu)\partial^\nu F_5(h) \]

\[ \mathcal{P}_6(h) = (\text{Tr}(V^\mu V^\nu))^2 F_6(h) \]

\[ \mathcal{P}_7(h) = \text{Tr}(V^\mu V^\nu)\partial_\nu \partial^\nu F_7(h) \]

\[ \mathcal{P}_8(h) = \text{Tr}(V^\mu V^\nu)\partial^\mu F_8(h)\partial^\nu F_8'(h) \]

\[ \mathcal{P}_9(h) = \text{Tr}((D_\mu V^\mu)^2)F_9(h) \]

\[ \mathcal{P}_{10}(h) = \text{Tr}(V_\nu D_\mu V^\mu)\partial^\nu F_{10}(h) \]

\[ \mathcal{P}_\square H = \frac{1}{v^2} (\partial_\mu \partial^\mu h)^2 F_\square H(h) \]

\[ \mathcal{P}_{11}(h) = (\text{Tr}(V^\mu V_\nu))^2 F_{11}(h) \]

\[ \mathcal{P}_{12}(h) = g^2 (\text{Tr}(TW_{\mu\nu}))^2 F_{12}(h) \]

\[ \mathcal{P}_{13}(h) = ig \text{Tr}(TW_{\mu\nu})\text{Tr}(T[V^\mu, V^\nu])F_{13}(h) \]

\[ \mathcal{P}_{14}(h) = g\varepsilon^{\mu\nu\rho\lambda} \text{Tr}(TV^\mu)\text{Tr}(V^\nu W_{\rho\lambda})F_{14}(h) \]

\[ \mathcal{P}_{15}(h) = \text{Tr}(TD_\mu V^\mu)\text{Tr}(TD_\nu V^\nu)F_{15}(h) \]

\[ \mathcal{P}_{16}(h) = \text{Tr}([T, V_\nu]D_\mu V^\mu)\text{Tr}(TV^\nu)F_{16}(h) \]

\[ \mathcal{P}_{17}(h) = ig \text{Tr}(TW_{\mu\nu})\text{Tr}(TV^\mu)\partial^\nu F_{17}(h) \]

\[ \mathcal{P}_{18}(h) = \text{Tr}(T[V^\mu, V_\nu])\text{Tr}(TV^\mu)\partial^\nu F_{18}(h) \]

\[ \mathcal{P}_{19}(h) = \text{Tr}(TD_\mu V^\mu)\text{Tr}(TV_\nu)\partial^\nu F_{19}(h) \]

\[ \mathcal{P}_{20}(h) = \text{Tr}(V^\mu V^\nu)\partial_\nu F_{20}(h)\partial^\nu F_{20}'(h) \]

\[ \mathcal{P}_{21}(h) = (\text{Tr}(TV^\mu))^2 \partial_\nu F_{21}(h)\partial^\nu F_{21}'(h) \]

\[ \mathcal{P}_{22}(h) = \text{Tr}(TV^\mu)\text{Tr}(TV_\nu)\partial^\mu F_{22}(h)\partial^\nu F_{22}'(h) \]

\[ \mathcal{P}_{23}(h) = \text{Tr}(V^\mu V^\nu)(\text{Tr}(TV_\nu))^2 F_{23}(h) \]

\[ \mathcal{P}_{24}(h) = \text{Tr}(V^\mu V_\nu)\text{Tr}(TV^\mu)\text{Tr}(TV^\nu)F_{24}(h) \]

\[ \mathcal{P}_{25}(h) = (\text{Tr}(TV^\mu))^2 \partial_\nu \partial^\nu F_{25}(h) \]

\[ \mathcal{P}_{26}(h) = (\text{Tr}(TV^\mu)\text{Tr}(TV_\nu))^2 F_{26}(h) \]

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Juan González Fraile (UB)  Johns Hopkins 2014  Heidelberg, July 2014  17 / 23
Disentangling a dynamical Higgs

Decorrelating Higgs and TGV

In the linear case

$$O_B = \frac{ieg^2}{8} A_{\mu \nu} W^{-\mu} W^{+\nu} (v + h)^2 - \frac{ie^2 g}{8 \cos \theta_W} Z_{\mu \nu} W^{-\mu} W^{+\nu} (v + h)^2$$

$$- \frac{eg}{4 \cos \theta_W} A_{\mu \nu} Z^\mu \partial^\nu h (v + h) + \frac{e^2}{4 \cos^2 \theta_W} Z_{\mu \nu} Z^\mu \partial^\nu h (v + h)$$

Higgs-TGV Correlated!

whereas in the non-linear case

$$P_2(h) = 2ieg^2 A_{\mu \nu} W^{-\mu} W^{+\nu} F_2(h) - 2 \frac{ie^2 g}{\cos \theta_W} Z_{\mu \nu} W^{-\mu} W^{+\nu} F_2(h)$$

$$P_4(h) = - \frac{eg}{\cos \theta_W} A_{\mu \nu} Z^\mu \partial^\nu F_4(h) + \frac{e^2}{\cos^2 \theta_W} Z_{\mu \nu} Z^\mu \partial^\nu F_4(h)$$

Higgs-TGV may be decorrelated!

---

$^4$ Parallel reasoning applies to $O_W$ and $P_3 - P_5$
Disentangling a dynamical Higgs

Decorrelating Higgs and TGV

Analysis using Higgs and TGV data\(^5\) of

\[ \mathcal{P}_G, \mathcal{P}_B, \mathcal{P}_W, \mathcal{P}_1, \mathcal{P}_2, \mathcal{P}_3, \mathcal{P}_4, \mathcal{P}_5, \mathcal{P}_C, \mathcal{P}_T \text{ and } \mathcal{P}_H, \]

After taking into consideration tree level contributions of \(\mathcal{P}_T\) and \(\mathcal{P}_1\) to EWPD, the relevant parameters for the analysis are\(^6\):

\[ a_G, a_B, a_W, c_2, c_3, a_4, a_5, (2a_c - c_C) \text{ and } c_H, \]

But we can rotate instead to:

\[ a_G, a_B, a_W, \Sigma_B, \Delta_B, \Sigma_W, \Delta_W, (2a_c - c_C) \text{ and } c_H, \]

where

\[ \Sigma_B \equiv 4(2c_2 + a_4), \quad \Sigma_W \equiv 2(2c_3 - a_5), \]

\[ \Delta_B \equiv 4(2c_2 - a_4), \quad \Delta_W \equiv 2(2c_3 + a_5), \]

defined such that at order \(d = 6\) of the linear regime \(\Sigma_B = c_B, \Sigma_W = c_W, \text{ while } \Delta_B = \Delta_W = 0.\)

---

\(^5\)The analysis details as in the linear fit

\(^6\)For simplicity here \(a_i = c_i \ast a_i\)
Disentangling a dynamical Higgs

Decorrelating Higgs and TGV

Left: A BSM sensor irrespective of the type of expansion: constraints from TGV and Higgs data on the combinations $\Sigma_B = 4(2c_2 + a_4)$ and $\Sigma_W = 2(2c_3 - a_5)$, which converge to $c_B$ and $c_W$ in the linear $d = 6$ limit.

Right: A non-linear versus linear discriminator: constraints on the combinations $\Delta_B = 4(2c_2 - a_4)$ and $\Delta_W = 2(2c_3 + a_5)$, which would take zero values in the linear (order $d = 6$) limit (as well as in the SM), indicated by the dot at $(0, 0)$. 
Higher order differences

Reshuffling → interactions that are strongly suppressed in one case may be leading corrections in the other.

More on TGV!

- At first order in non-linear expansion (but at dim–8 in the linear one) $P_{14}$ contributes to anomalous TGV: $g_5^Z$ (C- and P-odd but CP even).

$$\mathcal{L}_{WWV} = -ig_5^V \epsilon^{\mu \nu \rho \sigma} \left( W^+_{\mu} \partial_\rho W^-_\nu - W^-_{\nu} \partial_\rho W^+_{\mu} \right) V_\sigma$$

$$\rightarrow -\xi^2 \frac{g^3}{\cos \theta_W} \epsilon^{\mu \nu \rho \lambda} \left[p_+ + p_-\right]$$

- At first order in the linear expansion

$$\mathcal{O}_{WWW} = i \epsilon_{ijk} \hat{W}_{\mu}^{i, \nu} \hat{W}_{\rho}^{j, \nu} \hat{W}_{\rho}^{k, \mu}$$

gives contribution to anomalous TGV $\lambda_V$

- Chiral expansion: several operators contribute to QGVs without inducing TGVs → coefficients less constrained at present (larger deviations may be expected).

Linear expansion: modifications of QGVs that do not induce changes to TGVs appear only when $d = 8$. 
Relaxing assumptions: \( CP \)–odd

- List & applications of \( CP \)–odd non–linear operators:
  \[
  \mathcal{L}_{\text{chiral}} = \mathcal{L}_{SM} + \Delta \mathcal{L}_{CP},
  \]
  \[
  \Delta \mathcal{L}_{CP} = c_{\tilde{B}} S_{\tilde{B}}(h) + c_{\tilde{W}} S_{\tilde{W}}(h) + c_{\tilde{G}} S_{\tilde{G}}(h) + c_{2D} S_{2D}(h) + \sum_{i=1}^{16} c_i S_i(h).
  \]

- Use \( CP \)–odd sensitive signals
Relaxing assumptions: $CP$–odd

- List & applications of $CP$–odd non–linear operators:
  \[
  \mathcal{L}_{\text{chiral}} = \mathcal{L}_{SM} + \Delta \mathcal{L}_{CP},
  \]
  \[
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  \]

- Use $CP$–odd sensitive signals:

  Fermionic **EDMs** (sensitive to $\bar{\kappa}_\gamma$, $\bar{g}_h h \gamma$)

  ![Diagram](image)
Relaxing assumptions: \(CP\)–odd

List & applications of \(CP\)–odd non–linear operators:

\[
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\]

Use \(CP\)–odd sensitive signals:

- Fermionic EDMs (sensitive to \(\tilde{\kappa}_\gamma, \tilde{g}_h\gamma\gamma\))

\[
\begin{align*}
\gamma & \quad q \\
W & \quad p_1 \\
\gamma & \quad W \\
f & \quad p_2
\end{align*}
\]

\(CP\)–violating TGV

\[
\text{at 14 TeV} \quad 300 \text{ fb}^{-1}
\]
Relaxing assumptions

List & applications of CP–odd non–linear operators:

\[ \mathcal{L}_{\text{chiral}} = \mathcal{L}_{SM} + \Delta \mathcal{L}_{CP}, \]

\[ \Delta \mathcal{L}_{CP} = c_{\tilde{B}} S_{\tilde{B}}(h) + c_{\tilde{W}} S_{\tilde{W}}(h) + c_{\tilde{G}} S_{\tilde{G}}(h) + c_{2D} S_{2D}(h) + \sum_{i=1}^{16} c_i S_i(h). \]

Use CP–odd sensitive signals:

Fermionic EDMs (sensitive to \( \tilde{\kappa}_\gamma, \tilde{g}_h \gamma \gamma \))

\[ C_P-\text{violating TGV} \]

\[ C_P-\text{violation on Higgs physics: } h \to ZZ, \text{ e. g. } \text{CMS analysis:} \]

\[ A(h \to ZZ) = \frac{1}{v} \left( d_1 m_Z^2 \epsilon_1^* \epsilon_2^* + d_2 f_{\mu \nu}^{(1)} f_{\mu \nu}^{* (2)} + d_3 f_{\mu \nu}^{* (1)} \tilde{f}_{\mu \nu}^{* (2)} \right), \]
Conclusions

- **Model independent** analysis where the effects of new physics in the Higgs couplings are parametrized in $\mathcal{L}_{\text{eff}}$. If $SU(2)_L$ doublet $\rightarrow SU(2)_L \times U(1)_Y$ gauge symmetry linearly realized:

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n ,$$

- **Power to the data** $\rightarrow$ operators whose coefficients are more easily related to existing data.

  So far $\rightarrow$ Higgs boson SM–like.

- Exploit interesting **complementarity between experimental searches**: TGV and Higgs data.

- Study non–linear or chiral Lagrangian $\rightarrow$ more freedom $\rightarrow$ Testable decorrelations!

- In addition, promising new signals specific for one of the expansions: $g_5^Z$.

  arXiv:1207.1344, 1211.4580, 1304.1151, 1311.1823

- Study non–linear CP–odd operators $\rightarrow$ Recently finished: arxiv:1406.6367

- Combine the full Higgs and TGV 7+8 TeV sets of data in this framework.

- Jump from signal strengths to exploit the **kinematic** structures
Conclusions

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