Effective Lagrangian approach to the EWSB sector

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arXiv:1311.1823

Outline: accessing the EWSB mechanism

- Higgs boson discovery $\rightarrow$ **A particle directly related to the EWSB.**

  Its study is an alternative to the direct seek for new resonances.

- Huge variety of data $\rightarrow$ Higgs analysis, TGV, EWPD...

- Decipher the nature of the EWSB mechanism $\rightarrow$ 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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Model independent parametrization
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Indirect approach / Model independent parametrization	→	**EFFECTIVE LAGRANGIAN APPROACH!**	→	**Outline** 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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- 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**.

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The right of choice

Higgs interactions with gauge bosons[2]:

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \; G^a_{\mu\nu} G^{a\mu\nu} \;, \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \;, \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \;,$$

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TGV, Z properties, W decays, low energy ν scattering, atomic P, FCNC, Moller scattering P and $e^+ e^- \to f\bar{f}$ at LEP2 and

tree level contribution to the oblique parameters: must avoid blind directions.

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

$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W-f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB}-2c^2 f_{WW}]}{2c} \; ,$$

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

$$g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW} \; ,$$

$$g^f_{Hij} = -\frac{m^f_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}f'_{f\Phi,ij} \quad , g^{\Phi,2}_{Hxx} = g^{SM}_{Hxx}\left(1-\frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$

Effective Lagrangian for Higgs Interactions

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

Unitary gauge:

$$\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\, HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\, HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\, HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\, HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\, HZ_\mu Z^\mu \\
&+ +g^{(1)}_{HWW}\left(W^+_{\mu\nu}W^{-\,\mu}\partial^\nu H + \text{h.c.}\right) + g^{(2)}_{HWW}\, HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\, HW^+_\mu W^{-\,\mu}
\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar{f}'_L f'_R H + \text{h.c.}$$

$$\begin{aligned}
g_{Hgg} &= -\frac{\alpha_s}{8\pi}\frac{f_g v}{\Lambda^2} &, g_{H\gamma\gamma} &= -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}+f_{BB}}{2}, \\
g^{(1)}_{HZ\gamma} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} &, g^{(2)}_{HZ\gamma} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c}, \\
g^{(1)}_{HZZ} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} &, g^{(2)}_{HZZ} &= -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2}, \\
g^{(1)}_{HWW} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} &, g^{(2)}_{HWW} &= -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW}, \\
g^f_{Hij} &= -\frac{m^f_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} f'_{f\Phi,ij} &, g^{\Phi,2}_{Hxx} &= g^{SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)
\end{aligned}$$

Effective Lagrangian for Higgs Interactions

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

Unitary gauge:

$$\begin{aligned}\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\, HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\, HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\, HA_{\mu\nu}Z^{\mu\nu} \\ &+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\, HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\, HZ_\mu Z^\mu \\ &+ +g^{(1)}_{HWW}\left(W^+_{\mu\nu}W^{-\,\mu}\partial^\nu H + \text{h.c.}\right) + g^{(2)}_{HWW}\, HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\, HW^+_\mu W^{-\,\mu}\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar{f}'_L f'_R H + \text{h.c.}$$

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

$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s[2s^2 f_{BB} - 2c^2 f_{WW}]}{2c} \;,$$

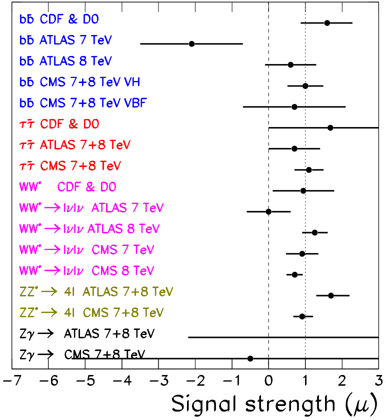
$$g^{(1)}_{HZZ} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} \quad , g^{(2)}_{HZZ} = -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2} \;,$$

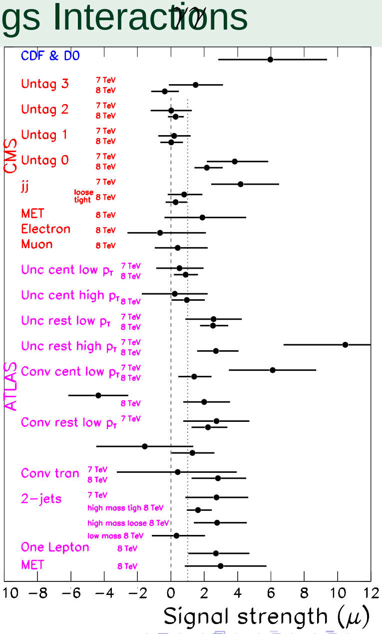
$$g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW} \;,$$

$$g^f_{Hij} = -\frac{m^f_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} f'_{f\Phi,ij} \quad , g^{\Phi,2}_{Hxx} = g^{SM}_{Hxx}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$

Effective Lagrangian for Higgs Interactions

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





TGV and EWPD

TGV:

$$\mathcal{L}_{WWV} = -ig_{WWV}\left\{ g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\,\nu\rho} V_\rho{}^\mu \right\}$$

$$\begin{aligned} \Delta g_1^Z &= g_1^Z - 1 = \frac{g^2 v^2}{8c^2\Lambda^2} f_W \ , \\ \Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2}\left(f_W + f_B \right) \ , \quad \leftrightarrow \\ \Delta\kappa_Z &= \kappa_Z - 1 = \frac{g^2 v^2}{8c^2\Lambda^2}\left(c^2 f_W - s^2 f_B \right) \ . \end{aligned}$$

$$g_1^Z = 0.984^{+0.049}_{-0.049} \qquad \text{LEP}$$

$$\kappa_\gamma = 1.004^{+0.024}_{-0.025} \qquad \rho = 0.11$$

EWPD:

$$\Delta S = 0.00 \pm 0.10 \qquad \Delta T = 0.02 \pm 0.11 \qquad \Delta U = 0.03 \pm 0.09$$

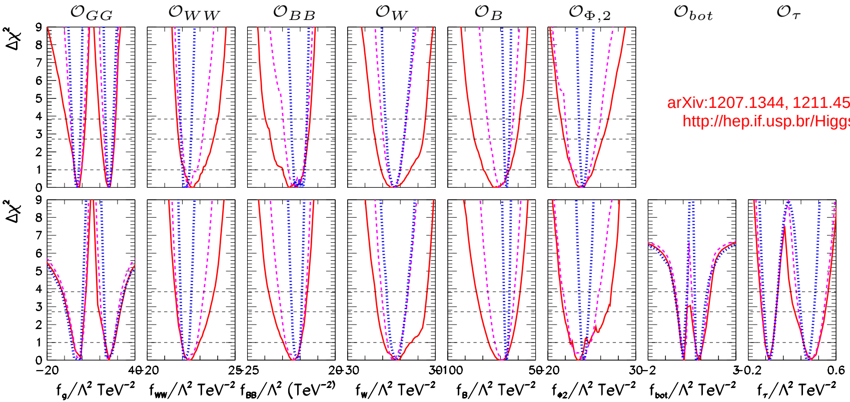
$$\rho = \begin{pmatrix} 1 & 0.89 & -0.55 \\ 0.89 & 1 & -0.8 \\ -0.55 & -0.8 & 1 \end{pmatrix}$$

$\mathcal{O}_{BW}$ and $\mathcal{O}_{\Phi,1}$ 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.

$\Delta\chi^2$ vrs f_X

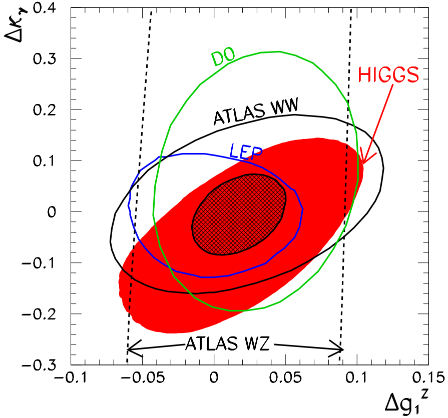


arXiv:1207.1344, 1211.4580
http://hep.if.usp.br/Higgs

Determining TGV from Higgs data

arxiv:1304.1151

- Gauge Invariance $\rightarrow$ TGV and Higgs couplings related: $\mathcal{O}_W$ and $\mathcal{O}_B$
- **Complementarity in experimental searches**: Higgs data bounds on $f_W \otimes f_B \equiv \Delta\kappa_\gamma \otimes \Delta g_1^Z$



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

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

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

Correlation between TGV and Higgs signals

$$\mathcal{L}_{WWV} = -ig_{WWV}\Big\{ g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} \Big\}$$

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

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

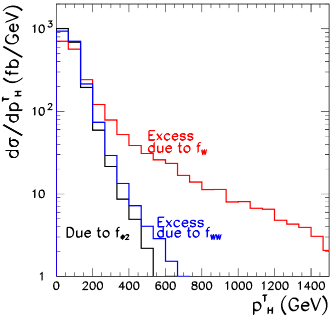
$$\Delta\kappa_Z = \frac{g^2 v^2}{8c^2\Lambda^2}\left(c^2 f_W - s^2 f_B \right) \ .$$

$$\mathcal{L}_{\rm eff}^{\rm HWW} = +g^{(1)}_{HWW}\left(W^+_{\mu\nu} W^{-\,\mu}\partial^\nu H + {\rm h.c.}\right) + g^{(2)}_{HWW}\ HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\ HW^+_\mu W^{-\,\mu}$$

$$g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \ ,$$

$$g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW} \ ,$$

$$g^{(3)}_{HWW} = g^{SM}_{HWW}\left(1 - \frac{v^2}{2}\frac{f_{\Phi,2}}{\Lambda^2}\right)$$



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

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

$\Rightarrow$ but with a distorted H p_T spectrum!

Disentangling a dynamical Higgs

arxiv:1311.1823

- Motivated by composite models $\rightarrow$ Higgs as a PGB of a global symmetry.
- Non-linear or "chiral" effective Lagrangian expansion including the light Higgs.

SM Gauge bosons and fermions

Light Higgs $\rightarrow$ without a given model treated as generic "singlet" h

$F_i(h) = 1 + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \dots$ $\leftrightarrow$ h is not part of Φ
More possible operators

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

$(\mathrm{V}_\mu \equiv (\mathrm{D}_\mu \mathrm{U})\,\mathrm{U}^\dagger$ and $\mathrm{T} \equiv \mathrm{U}\sigma_3\mathrm{U}^\dagger)$ $\leftrightarrow$ Relative reshuffling of the order at which operators appear

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

Bosonic (pure gauge and gauge-h operators) and Yukawa-like up to four derivatives[3]

$$\begin{aligned}\Delta\mathcal{L} &= \xi\,[c_B\mathcal{P}_B(h) + c_W\mathcal{P}_W(h) + c_G\mathcal{P}_G(h) + c_C\mathcal{P}_C(h) + c_T\mathcal{P}_T(h) + c_H\mathcal{P}_H(h) + c_{\Box H}\mathcal{P}_{\Box H}(h)] \\ &+ \xi\sum_{i=1}^{10} c_i\mathcal{P}_i(h) + \xi^2\sum_{i=11}^{25} c_i\mathcal{P}_i(h) + \xi^4 c_{26}\mathcal{P}_{26}(h) + \Sigma_i\xi^{n_i} c^i_{HH}\mathcal{P}^i_{HH}(h)\end{aligned}$$

[3] $\mathrm{D}_\mu\mathrm{U}(x) \equiv \partial_\mu\mathrm{U}(x) + igW_\mu(x)\mathrm{U}(x) - \frac{ig'}{2}B_\mu(x)\mathrm{U}(x)\sigma_3$

$\mathbf{Y}_Q \equiv \mathbf{diag}\,(Y_U,\, Y_D)\,,\qquad \mathbf{Y}_L \equiv \mathbf{diag}\,(Y_\nu,\, Y_L)\,.$

The Non-linear Lagrangian

Alonso *et al* 1212.3305

$$\mathcal{P}_C(h) = -\frac{v^2}{4}\mathrm{Tr}(\mathbf{V}^\mu\mathbf{V}_\mu)\mathcal{F}_C(h)$$
$$\mathcal{P}_T(h) = \frac{v^2}{4}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathcal{F}_T(h)$$
$$\mathcal{P}_H(h) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\mathcal{F}_H(h)$$
$$\mathcal{P}_B(h) = -\frac{g'^2}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B(h)$$
$$\mathcal{P}_W(h) = -\frac{g^2}{4}W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W(h)$$
$$\mathcal{P}_G(h) = -\frac{g_s^2}{4}G^a_{\mu\nu}G^{a\mu\nu}\mathcal{F}_G(h)$$
$$\mathcal{P}_1(h) = gg'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1(h)$$
$$\mathcal{P}_2(h) = ig'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2(h)$$
$$\mathcal{P}_3(h) = ig\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3(h)$$
$$\mathcal{P}_4(h) = ig'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4(h)$$
$$\mathcal{P}_5(h) = ig\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5(h)$$
$$\mathcal{P}_6(h) = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6(h)$$
$$\mathcal{P}_7(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\partial^\nu\mathcal{F}_7(h)$$
$$\mathcal{P}_8(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\partial^\mu\mathcal{F}_8(h)\partial^\nu\mathcal{F}'_8(h)$$
$$\mathcal{P}_9(h) = \mathrm{Tr}((\mathcal{D}_\mu\mathbf{V}^\mu)^2)\mathcal{F}_9(h)$$
$$\mathcal{P}_{10}(h) = \mathrm{Tr}(\mathbf{V}_\nu\mathcal{D}_\mu\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{10}(h)$$
$$\mathcal{P}_{\Box H} = \frac{1}{v^2}(\partial_\mu\partial^\mu h)^2\mathcal{F}_{\Box H}(h)\,.$$

$$\mathcal{P}_{11}(h) = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}(h)$$
$$\mathcal{P}_{12}(h) = g^2(\mathrm{Tr}(\mathbf{T}W_{\mu\nu}))^2\mathcal{F}_{12}(h)$$
$$\mathcal{P}_{13}(h) = ig\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_{13}(h)$$
$$\mathcal{P}_{14}(h) = g\varepsilon^{\mu\nu\rho\lambda}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}(h)$$
$$\mathcal{P}_{15}(h) = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathcal{D}_\nu\mathbf{V}^\nu)\mathcal{F}_{15}(h)$$
$$\mathcal{P}_{16}(h) = \mathrm{Tr}([\mathbf{T},\mathbf{V}_\nu]\mathcal{D}_\mu\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{16}(h)$$
$$\mathcal{P}_{17}(h) = ig\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18}(h) = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu,\mathbf{V}_\nu])\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18}(h)$$
$$\mathcal{P}_{19}(h) = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\partial^\nu\mathcal{F}_{19}(h)$$
$$\mathcal{P}_{20}(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\mathcal{F}_{20}(h)\partial^\nu\mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2\partial_\nu\mathcal{F}_{21}(h)\partial^\nu\mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22}(h) = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\partial^\mu\mathcal{F}_{22}(h)\partial^\nu\mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23}(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24}(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2\partial_\nu\partial^\nu\mathcal{F}_{25}(h)$$
$$\mathcal{P}_{26}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{26}(h)$$

The Non-linear Lagrangian

Alonso *et al* 1212.3305

$$\mathcal{P}_C(h) = -\frac{v^2}{4}\mathrm{Tr}(\mathbf{V}^\mu\mathbf{V}_\mu)\mathcal{F}_C(h)$$
$$\mathcal{P}_T(h) = \frac{v^2}{4}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathcal{F}_T(h)$$
$$\mathcal{P}_H(h) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\mathcal{F}_H(h)$$
$$\mathcal{P}_B(h) = -\frac{g'^2}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B(h)$$
$$\mathcal{P}_W(h) = -\frac{g^2}{4}W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W(h)$$
$$\mathcal{P}_G(h) = -\frac{g_s^2}{4}G^a_{\mu\nu}G^{a\mu\nu}\mathcal{F}_G(h)$$
$$\mathcal{P}_1(h) = gg'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1(h)$$
$$\mathcal{P}_2(h) = ig'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2(h)$$
$$\mathcal{P}_3(h) = ig\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3(h)$$
$$\mathcal{P}_4(h) = ig'B_{\mu\nu}\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4(h)$$
$$\mathcal{P}_5(h) = ig\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5(h)$$
$$\mathcal{P}_6(h) = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6(h)$$
$$\mathcal{P}_7(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\partial^\nu\mathcal{F}_7(h)$$
$$\mathcal{P}_8(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\partial^\mu\mathcal{F}_8(h)\partial^\nu\mathcal{F}'_8(h)$$
$$\mathcal{P}_9(h) = \mathrm{Tr}((\mathcal{D}_\mu\mathbf{V}^\mu)^2)\mathcal{F}_9(h)$$
$$\mathcal{P}_{10}(h) = \mathrm{Tr}(\mathbf{V}_\nu\mathcal{D}_\mu\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{10}(h)$$
$$\mathcal{P}_{\Box H} = \frac{1}{v^2}(\partial_\mu\partial^\mu h)^2\mathcal{F}_{\Box H}(h)\,.$$

$$\mathcal{P}_{11}(h) = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}(h)$$
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$$\mathcal{P}_{16}(h) = \mathrm{Tr}([\mathbf{T},\mathbf{V}_\nu]\mathcal{D}_\mu\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{16}(h)$$
$$\mathcal{P}_{17}(h) = ig\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}(h)$$
$$\mathcal{P}_{18}(h) = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu,\mathbf{V}_\nu])\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18}(h)$$
$$\mathcal{P}_{19}(h) = \mathrm{Tr}(\mathbf{T}\mathcal{D}_\mu\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\partial^\nu\mathcal{F}_{19}(h)$$
$$\mathcal{P}_{20}(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\mathcal{F}_{20}(h)\partial^\nu\mathcal{F}'_{20}(h)$$
$$\mathcal{P}_{21}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2\partial_\nu\mathcal{F}_{21}(h)\partial^\nu\mathcal{F}'_{21}(h)$$
$$\mathcal{P}_{22}(h) = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\partial^\mu\mathcal{F}_{22}(h)\partial^\nu\mathcal{F}'_{22}(h)$$
$$\mathcal{P}_{23}(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{23}(h)$$
$$\mathcal{P}_{24}(h) = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{24}(h)$$
$$\mathcal{P}_{25}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2\partial_\nu\partial^\nu\mathcal{F}_{25}(h)$$
$$\mathcal{P}_{26}(h) = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{26}(h)$$

Decorrelating Higgs and TGV

arxiv:1311.1823

In the linear case[4]

$$\left.\begin{aligned} \mathcal{O}_B \quad = \quad & \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 \\ & - \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^{\mu} \partial^{\nu} h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^{\mu} \partial^{\nu} h (v+h) \end{aligned}\right\} \text{Higgs-TGV Correlated}$$

whereas in the non-linear case

$$\left.\begin{aligned} \mathcal{P}_2(h) \quad &= \quad 2ieg^2 A_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) - 2\frac{ie^2 g}{\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) \\ \mathcal{P}_4(h) \quad &= \quad -\frac{eg}{\cos\theta_W} A_{\mu\nu} Z^{\mu} \partial^{\nu} \mathcal{F}_4(h) + \frac{e^2}{\cos^2\theta_W} Z_{\mu\nu} Z^{\mu} \partial^{\nu} \mathcal{F}_4(h) \end{aligned}\right\} \text{Higgs-TGV may be decorrelated!}$$

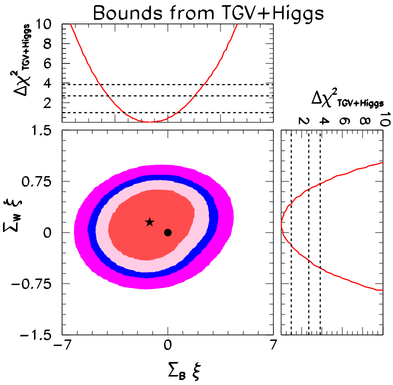
Analysis of Higgs + TGV data, defining as new coefficients

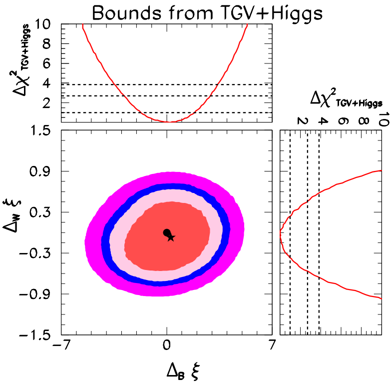
$$\Sigma_B \equiv 4(2c_2 + a_4)\,, \qquad \Sigma_W \equiv 2(2c_3 - a_5)\,,$$
$$\Delta_B \equiv 4(2c_2 - a_4)\,, \qquad \Delta_W \equiv 2(2c_3 + a_5)\,,$$

defined such that at order $d = 6$ of the linear regime $\Sigma_B = c_B$, $\Sigma_W = c_W$, while $\Delta_B = \Delta_W = 0$.

[4] Parallel reasoning applies to $\mathcal{O}_W$ and $\mathcal{P}_3 - \mathcal{P}_5$

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

arxiv:1311.1823

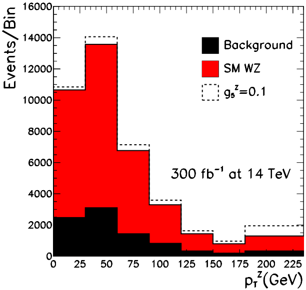
Reshuffling $\rightarrow$ interactions that are strongly suppressed in one case may be leading corrections in the other.

More on TGV!

- At *first* order in non-linear expansion (but at dim–8 in the linear one) $\mathcal{P}_{10}$ contributes to anomalous TGV: g_5^Z (C- and P-odd but CP even).

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

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



- At first order in the linear expansion $\mathcal{O}_{WWW} = i\epsilon_{ijk} \hat{W}_\mu^{i\,\nu} \hat{W}_\nu^{j\,\rho} \hat{W}_\rho^{k\,\mu}$ gives contribution to anomalous TGV λ_V

- Chiral expansion: several operators contribute to QGVs without inducing TGVs $\rightarrow$ 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 $d = 8$.

Conclusions

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

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

- **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

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THANK YOU!

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