Effective Lagrangians for Higgs Physics

Tyler Corbett

YITP, SUNY Stony Brook

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T.C., O.J.P. Éboli, J. Gonzalez–Fraile, M.C. Gonzalez–Garcia
I. Brivio, M.B. Gavela, L. Merlo, and S. Rigolin
Two Approaches

We consider two different approaches within Effective Field Theory (EFT) to quantify Higgs physics Beyond the Standard Model (BSM).

<table>
<thead>
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<th>Chiral Expansion</th>
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Linear Expansion

We define:

\[ L_{\text{linear}} = L_{\text{SM}} + \Delta L_{\text{linear}} \]

\[ \Delta L_{\text{linear}} = \sum_{n>4} \sum_i f_i^{(n)} \frac{1}{\Lambda^{n-4}} O_i^{(n)} \]

To \( n=6 \): 9 CP-even, baryon and lepton number preserving Gauge-Higgs Operators\(^1\):

\[ O_{\text{GG}} = \Phi_\dagger G_{\mu\nu}^a G^{a\mu\nu} \]
\[ O_{\text{BB}} = \Phi_\dagger [\hat{B}_{\mu\nu}] \hat{B}^{\mu\nu} \Phi \]
\[ O_W = (D_\mu \Phi)\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \]
\[ O_{\Phi,1} = (D_\mu \Phi)\dagger \Phi \Phi\dagger (D_\mu \Phi) \]
\[ O_{\Phi,4} = (D_\mu \Phi)\dagger (D_\mu \Phi) (\Phi\dagger \Phi) \]

11 (\( \times 3 \) generations) fermionic operators (more if allowed to be non-flavor diagonal)

2 (currently) relevant to our analysis. (of the form \( \Phi_\dagger \Phi \bar{\Psi}_i \Phi \Psi_i \))

\( O_{\phi,1\&BW} \) and and fermionic operators also affecting \( Wff, Zff \), and/or flavor changing strongly constrained by precision data.

\( O_{\phi,4} \) can be moved to fermionic operators by EOM.

\(^1\) Additionally two Pure Higgs (\( O_{\phi,3\&\Box \phi} \)), and 5 pure gauge (\( O_{WWW\&GGG\&DW\&DB\&DG} \)), not relevant to this analysis.
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\mathcal{O}_{GG} &= \Phi^\dagger \Phi G_{\mu \nu} G^{a \mu \nu} \\
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\mathcal{O}_W &= (D_\mu \Phi)^\dagger \hat{W}^{\mu \nu} (D_\nu \Phi) \\
\mathcal{O}_{\Phi,1} &= (D_\mu \Phi)^\dagger \Phi (D_\mu \Phi) \\
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\end{align*}

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Effective Lagrangians

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To \( n=6 \): 9 CP-even, baryon and lepton number preserving Gauge-Higgs Operators\(^1\):

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\[ \mathcal{O}_{\text{BB}} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \]
\[ \mathcal{O}_{\text{WW}} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \]
\[ \mathcal{O}_{\text{BW}} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \]
\[ \mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \]
\[ \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) \]

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We define:

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

Then the effective Chiral Lagrangian (up to 4 derivatives) can be written as:

\[ \Delta \mathcal{L} = \xi [c_B \mathcal{P}_B(h) + c_W \mathcal{P}_W(h) + c_G \mathcal{P}_G(h) + c_C \mathcal{P}_C(h) + c_T \mathcal{P}_T(h) + c_H \mathcal{P}_H(h) + c_\Box \mathcal{P}_\Box(h)] \\
+ \xi \sum_{i=1}^{10} c_i \mathcal{P}_i(h) + \xi^2 \sum_{i=11}^{25} c_i \mathcal{P}_i + \xi^4 c_{26} \mathcal{P}_{26} + \cdots \]

Note: this expression should not be taken as a series in \( \xi \equiv (v/f)^2 \)

\( \xi \) is a useful variable for relating this series to the linear basis.

And now \( v \) and \( \langle h \rangle \) are not the same, but:

\[ v = g(f, \langle h \rangle) \]

Where: \( v \) is the gauge boson mass scale, \( \langle h \rangle \) is the EWSB scale, and \( f \) the characteristic goldstone boson scale.
Effective Lagrangians

Chiral Expansion II

Operators relevant to Higgs & Gauge boson processes at $O(\xi)$:

$$\Delta \mathcal{L} = \xi [c_B \mathcal{P}_B(h) + c_W \mathcal{P}_W(h) + c_G \mathcal{P}_G(h) + c_H \mathcal{P}_H(h) + c_C \mathcal{P}_C(h) + c_T \mathcal{P}_T(h) + c_1 \mathcal{P}_1(h) + c_2 \mathcal{P}_2(h) + c_3 \mathcal{P}_3(h) + c_4 \mathcal{P}_4(h) + c_5 \mathcal{P}_5(h)]$$

The above operators take the form:

$$\mathcal{P}_B(h) = -\frac{g'}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_W(h) = -\frac{g'}{4} W^a_{\mu\nu} W^{a\mu\nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_G(h) = -\frac{g}{4} G^a_{\mu\nu} G^{a\mu\nu} \mathcal{F}_G(h)$$
$$\mathcal{P}_H(h) = \frac{1}{2} (\partial_\mu h)(\partial_\mu h) \mathcal{F}_H(h)$$
$$\mathcal{P}_T(h) = \frac{v^2}{4} Tr(TV_{\mu}) Tr(TV^\mu) \mathcal{F}_T(h)$$
$$\mathcal{P}_1(h) = gg' B_{\mu\nu} Tr(TW^{\mu\nu}) \mathcal{F}_1(h)$$
$$\mathcal{P}_2(h) = ig' B_{\mu\nu} Tr(T[V^\mu, V^\nu]) \mathcal{F}_2(h)$$
$$\mathcal{P}_3(h) = ig Tr(W_{\mu\nu} [V^\mu, V^\nu]) \mathcal{F}_3(h)$$
$$\mathcal{P}_4(h) = ig' B_{\mu\nu} Tr(T[V^\mu, V^\nu]) \partial^\nu \mathcal{F}_4(h)$$
$$\mathcal{P}_5(h) = ig Tr(W_{\mu\nu} V^\mu) \partial^\nu \mathcal{F}_5(h)$$

$$V_\mu \equiv (D_\mu U) U^\dagger \quad T \equiv U\sigma_3 U^\dagger \quad U(x) \rightarrow LU(x)R^\dagger \quad U(x) = \exp(i\sigma_a \pi^a(x)/v)$$

For our phenomenological analysis we take$^2$:

$$c_i \mathcal{F}_i(h) = c_i + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \cdots$$

$^2$Note for $SU(2)$ $a_i = b_i = c_i$
Chiral Expansion II

Operators relevant to Higgs & Gauge boson processes at $O(\xi)$:

$$\Delta \mathcal{L} = \xi [c_B \mathcal{P}_B(h) + c_W \mathcal{P}_W(h) + c_G \mathcal{P}_G(h) + c_H \mathcal{P}_H(h) + c_C \mathcal{P}_C(h) + c_T \mathcal{P}_T(h) + c_1 \mathcal{P}_1(h) + c_2 \mathcal{P}_2(h) + c_3 \mathcal{P}_3(h) + c_4 \mathcal{P}_4(h) + c_5 \mathcal{P}_5(h)]$$

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$$\mathcal{P}_B(h) = -\frac{g'^2}{4} B_{\mu \nu} B^{\mu \nu} \mathcal{F}_B(h)$$
$$\mathcal{P}_W(h) = -\frac{g'^2}{4} W_{\mu \nu} W^{\mu \nu} \mathcal{F}_W(h)$$
$$\mathcal{P}_H(h) = \frac{1}{2} (\partial_\mu h)(\partial^\mu h) \mathcal{F}_H(h)$$
$$\mathcal{P}_T(h) = \frac{v^2}{4} Tr(TV_{\mu}) Tr(TV^{\mu}) \mathcal{F}_T(h)$$
$$\mathcal{P}_2(h) = ig' B_{\mu \nu} Tr(T[W_{\mu \nu}, V^\nu]) \mathcal{F}_2(h)$$
$$\mathcal{P}_4(h) = ig' B_{\mu \nu} Tr(TV^{\mu}) \partial^\nu \mathcal{F}_4(h)$$

Where:

$$V_{\mu} \equiv (D_{\mu} U) U^\dagger \quad T \equiv U \sigma_3 U^\dagger \quad U(x) \rightarrow L U(x) R^\dagger \quad U(x) = \exp(i \sigma_a \pi^a (x)/v)$$

For our phenomenological analysis we take\(^2\):

$$c_i \mathcal{F}_i(h) = c_i + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \cdots$$

\(^2\)Note for $SU(2)$ $a_i = b_i = c_i$
(Very) Brief Comparison of Bases

The order in $\xi$ of an operator demonstrates the minimum canonical dimension of a Linear operator necessary for comparison with the Chiral basis.

For small $\xi$ we can relate the Linear basis to the Chiral (more operators):

\begin{align*}
\mathcal{O}_{WW} &= \frac{g^2}{4} \Phi^\dagger W^{\mu\nu} W_{\mu\nu} \Phi \quad \rightarrow \quad \mathcal{P}_W = -\frac{g^2}{2} Tr(W_{\mu\nu} W^{\mu\nu}) \mathcal{F}_W(h) \\
\mathcal{O}_{BB} &= \frac{g}{4} \Phi^\dagger B^{\mu\nu} B_{\mu\nu} \Phi \quad \rightarrow \quad \mathcal{P}_B = -\frac{g}{4} Tr(B_{\mu\nu} B^{\mu\nu}) \mathcal{F}_B(h) \\
\mathcal{O}_{BW} &= \frac{g g'}{4} \Phi^\dagger B^{\mu\nu} W_{\mu\nu} \Phi \quad \rightarrow \quad \mathcal{P}_1 = g g' B_{\mu\nu} Tr(TW^{\mu\nu}) \mathcal{F}_1 \\
\mathcal{O}_B &= \frac{g'}{2} (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi) \quad \rightarrow \quad \mathcal{P}_2 = i g' B_{\mu\nu} Tr(T[V^\mu, V^\nu]) \mathcal{F}_2(h) \\
\mathcal{O}_W &= \frac{g}{2} (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi) \quad \rightarrow \quad \mathcal{P}_3 = i g Tr(W_{\mu\nu} [V^\mu, V^\nu]) \mathcal{F}_3(h) \\
\mathcal{O}_{\phi,1} &= (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D_\nu \Phi) \quad \rightarrow \quad \mathcal{P}_T = \frac{v^2}{4} Tr(TV_{\mu}) Tr(TV_{\mu}) \mathcal{F}_T(h) \\
\mathcal{O}_{\phi,2} &= \frac{1}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) \quad \rightarrow \quad \mathcal{P}_H = \frac{1}{2} (\partial_\mu h)(\partial^\mu h) \mathcal{F}_H(h) \\
\mathcal{O}_{\phi,4} &= (D_\mu \Phi)^\dagger (D_\nu \Phi) (\Phi^\dagger \Phi) \quad \rightarrow \quad \mathcal{P}_C = -\frac{v^2}{4} Tr(V_{\mu} V_{\mu}) \mathcal{F}_C
\end{align*}
(Very) Brief Comparison of Bases II

Each operator contributes to particular HVV and TGV vertices. In particular:

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{O}_{BB}$</th>
<th>$\mathcal{O}_{WW}$</th>
<th>$\mathcal{O}_B$</th>
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<th>$\mathcal{P}_B$</th>
<th>$\mathcal{P}_W$</th>
<th>$\mathcal{P}_2$</th>
<th>$\mathcal{P}_4$</th>
<th>$\mathcal{P}_3$</th>
<th>$\mathcal{P}_5$</th>
</tr>
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<tbody>
<tr>
<td>$h\gamma\gamma$</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$h\gamma Z$</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>$HW^+ W^-$</td>
<td></td>
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<td>x</td>
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<td>x</td>
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<tr>
<td>$\gamma W^+ W^-$</td>
<td>x</td>
<td>x</td>
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<td></td>
<td>x</td>
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<tr>
<td>$ZW^+ W^-$</td>
<td>x</td>
<td></td>
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Notice that green illustrates the decorrelation of TGV from Higgs data for:

$$\mathcal{O}_B = \frac{v^2}{16} \mathcal{P}_2 + \frac{v^2}{8} \mathcal{P}_4$$

And blue illustrates a similar decorrelation for:

$$\mathcal{O}_W = \frac{v^2}{8} \mathcal{P}_3 - \frac{v^2}{4} \mathcal{P}_5$$

$^3$ $\mathcal{O}_{\phi_4,\phi_2} (\mathcal{P}_{H,T})$ give shifts to all SM $HVV$ & $Hff$ vertices.
(Very) Brief Comparison of Bases II

Each operator contributes to particular HVV and TGV vertices. In particular\(^3\):

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\(^3\mathcal{O}_{\phi_4,\phi_2} (\mathcal{P}_{H,T})\) give shifts to all SM HVV & Hff vertices
Higgs Phenomenology in Linear Expansion

Constructing a $\chi^2$ fit to the data from LHC and TeVatron for the operators,

$$\{O_{GG} \quad O_{WW} \quad O_{BB} \quad O_W \quad O_B \quad O_{\phi,2}\}$$

And plotting $\Delta\chi^2$ as a function of each, marginalized over the others:

- Solid, Higgs Only
- Dashed, Higgs + TGV(LEP)
- Best fit near $f_i = 0$ (SM)

$Hgg$ degeneracy from $\frac{fg}{\Lambda^2} \sim -2$SM-loop

$H\gamma\gamma \rightarrow$ anticorrelation between $f_{WW}$ & $f_{BB}$

TGV $\rightarrow$ direct effect on $f_W$ & $f_B$
Higgs Phenomenology in Linear Expansion

Constructing a $\chi^2$ fit to the data from LHC and TeVatron for the operators,

$$\{\mathcal{O}_{GG}, \mathcal{O}_{WW}, \mathcal{O}_{BB}, \mathcal{O}_{W}, \mathcal{O}_{B}, \mathcal{O}_{\phi,2}\} \quad (\quad + \{\mathcal{O}_{\text{bot}}, \mathcal{O}_{\tau}\})$$

And plotting $\Delta \chi^2$ as a function of each, marginalized over the others:
Phenomenology

Higgs Phenomenology in Linear Expansion

Constructing a $\chi^2$ fit to the data from LHC and TeVatron for the operators,

$$\{\mathcal{O}_{GG}, \mathcal{O}_{WW}, \mathcal{O}_{BB}, \mathcal{O}_W, \mathcal{O}_B, \mathcal{O}_{\phi,2}\} \quad (\text{+} \quad \{\mathcal{O}_{\text{bot}}, \mathcal{O}_{\tau}\})$$

And plotting $\Delta^2$ as a function of each, marginalized over the others:

- Solid, Higgs Only
- Dashed, Higgs + TGV(LEP)

Fit with $f_g/f_{WW} = -f_{BB}, f_w, f_B, f_{\text{bot}}, f_s = 0$
### Higgs Phenomenology in Linear Expansion II

**Fit with** $f_{bot} = f_{\tau} = 0$

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Best fit</th>
<th>90% CL allowed range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_g/\Lambda^2$ (TeV$^{-2}$)</td>
<td>1.1, 22</td>
<td>$[-3.3, 5.1] \cup [19, 26]$</td>
</tr>
<tr>
<td>$f_{WW}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>1.5</td>
<td>$[-3.2, 8.2]$</td>
</tr>
<tr>
<td>$f_{BB}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>-1.6</td>
<td>$[-7.5, 5.3]$</td>
</tr>
<tr>
<td>$f_W/\Lambda^2$ (TeV$^{-2}$)</td>
<td>2.1</td>
<td>$[-5.6, 9.6]$</td>
</tr>
<tr>
<td>$f_B/\Lambda^2$ (TeV$^{-2}$)</td>
<td>-10</td>
<td>$[-29, 8.9]$</td>
</tr>
<tr>
<td>$f_{\phi,2}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>-1.0</td>
<td>$[-10, 8.5]$</td>
</tr>
<tr>
<td>$f_{bot}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$f_{\tau}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>—</td>
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**Fit with** $f_{bot}$ and $f_{\tau}$

<table>
<thead>
<tr>
<th>Coupling</th>
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<tbody>
<tr>
<td>$f_g/\Lambda^2$ (TeV$^{-2}$)</td>
<td>2.7, 21</td>
<td>$[-5.3, 5.8] \cup [17, 22]$</td>
</tr>
<tr>
<td>$f_{WW}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>0.37</td>
<td>$[-4.2, 7.7]$</td>
</tr>
<tr>
<td>$f_{BB}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>-0.37</td>
<td>$[-7.7, 4.2]$</td>
</tr>
<tr>
<td>$f_W/\Lambda^2$ (TeV$^{-2}$)</td>
<td>1.0</td>
<td>$[-5.4, 9.8]$</td>
</tr>
<tr>
<td>$f_B/\Lambda^2$ (TeV$^{-2}$)</td>
<td>-7.0</td>
<td>$[-28, 11]$</td>
</tr>
<tr>
<td>$f_{\phi,2}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>-0.58</td>
<td>$[-9.8, 7.5]$</td>
</tr>
<tr>
<td>$f_{bot}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>0.01, 0.83</td>
<td>$[-0.28, 0.24] \cup [0.55, 1.3]$</td>
</tr>
<tr>
<td>$f_{\tau}/\Lambda^2$ (TeV$^{-2}$)</td>
<td>-0.01, 0.37</td>
<td>$[-0.07, 0.05] \cup [0.26, 0.49]$</td>
</tr>
</tbody>
</table>

- SM predictions within 68% CL range for all couplings
- For LHC14 300/fb (3000/fb) expected improvement by factor $\sim 3 - 100$ (8 – 200)
TGV Constraints from Higgs Data in Linear Realization

Correlations between TGV & HVV in Linear basis → constraints on TGV from HVV Data,

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

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

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

Where,

\[
\mathcal{L}_{WVV} = -ig_{WVV} \left\{ g_1^V \left( W^+_{\mu\nu} W^-_{\mu} V^\nu - W^+_{\mu} V^\nu W^-_{\mu\nu} \right) + \kappa_V W^+_{\mu} W^-_{\nu} V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\mu\nu} W^{-\nu\rho} V^\mu_{\rho} \right\}
\]
A similar $\chi^2$ fit for the Chiral operators,\[ \mathcal{P}_G \; \mathcal{P}_4 \; \mathcal{P}_5 \; \mathcal{P}_B \; \mathcal{P}_W \; \mathcal{P}_H \]

Results in the following 1d (marginalized) distributions:

Solid, Higgs Only

*No TGV bounds*

Best fit near $c_i = 0$ (SM)

$Hgg$ degeneracy from $a_G \sim -2$SM-loop

$H\gamma\gamma \rightarrow$ anticorrelation between $a_W$ & $a_B$
Discriminating Linear from Chiral Realizations

Recalling the relation between $O_B$ and $P_2, P_4$ and $O_W$ and $P_3, P_5$:

$$O_B = \frac{v^2}{16} P_2 + \frac{v^2}{8} P_4 \quad O_W = \frac{v^2}{8} P_3 - \frac{v^2}{4} P_5$$

We define the discriminating quantities (using a similar relation for $O_W$ and $P_3, P_5$):

$$\Sigma_B \equiv 4(2c_2 + a_4) \quad \Sigma_W \equiv 2(2c_3 - a_5), \quad \Sigma_{B(W)} \rightarrow \frac{f_{B(W)} v^2}{\Lambda^2} \quad \text{(Linear limit)}$$

$$\Delta_B \equiv 4(2c_2 - a_4) \quad \Delta_W \equiv 2(2c_3 + a_5), \quad \Delta_B = \Delta_W \rightarrow 0$$
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$$\Delta_B \equiv 4(2c_2 - a_4) \quad \Delta_W \equiv 2(2c_3 + a_5), \quad \Delta_B = \Delta_W \rightarrow 0$$
Conclusions

- We apply the methodology of Effective Field Theory to both Linear and Chiral realizations of SU(2)$_L \times$ U(1)$_Y$ gauge symmetry breaking.

- We perform a global fit to all relevant data and obtain bounds on the coefficients of operators in both realizations.

- In Linear expansion HVV $\Leftrightarrow$ TGV
  In Chiral expansion HVV & TGV decorrelated

- We have constructed observables to discriminate between these two expansions.