Effective Lagrangians for Higgs Physics

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arXiv:1311.1823 (JHEP)
1304.1151 (PRL)
1211.4580 (PRD)
1207.1344 (PRD)

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Two Approaches

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

	Linear Expansion	Chiral Expansion
Higgs Type:	Elementary	Composite (e.g. pseudo GS boson)
Scale of NP:	$\Lambda_{\rm NP}$, new mass scale	$\Lambda_{\rm S}$, scale at which a new global symmetry is exact
Applicability:	e.g. SUSY models	Composite Higgs Models, Little Higgses, Higher D Models
Symmetry:	h part of $SU(2)_{\rm L}$ doublet, Φ	h not part of doublet, but singlet
Truncation:	at Dimension 6 operators, i.e. $1/\Lambda_{\rm NP}^2$	4 derivatives

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Linear Expansion

We define:

$$\mathcal{L}_{\text{linear}} = \mathcal{L}_{\text{SM}} + \Delta\mathcal{L}_{\text{linear}} \qquad \Delta\mathcal{L}_{\text{linear}} = \sum_{n>4}\sum_i \frac{f_i^{(n)}}{\Lambda^{n-4}}\mathcal{O}_i^{(n)}$$

To n=6: 9 CP-even, baryon and lepton number preserving Gauge-Higgs Operators[1]:

$$\begin{array}{lcllcl}
\mathcal{O}_{\rm GG} & = & \Phi^\dagger\Phi G^a_{\mu\nu}G^{a\mu\nu} & \mathcal{O}_{\rm WW} & = & \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \\
\mathcal{O}_{\rm BB} & = & \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi & \mathcal{O}_{\rm BW} & = & \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \\
\mathcal{O}_{\rm W} & = & (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi) & \mathcal{O}_{\rm B} & = & (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi) \\
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\mathcal{O}_{\Phi,4} & = & (D_\mu\Phi)^\dagger(D_\mu\Phi)(\Phi^\dagger\Phi) & & &
\end{array}$$

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

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

$\mathcal{O}_{\phi,1\&\rm BW}$ and and fermionic operators also affecting Wff,Zff, and/or flavor changing strongly constrained by precision data.

$\mathcal{O}_{\phi,4}$ can be moved to fermionic operators by EOM.

[1] Additionally two Pure Higgs ($\mathcal{O}_{\phi,3\&\Box\phi}$),
and 5 pure gauge ($\mathcal{O}_{\rm WWW\&GGG\&DW\&DB\&DG}$), not relevant to this analysis.

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Chiral Expansion

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:

$$\begin{aligned}\Delta\mathcal{L} = \xi[&c_{\text{B}}\mathcal{P}_{\text{B}}(h) + c_{\text{W}}\mathcal{P}_{\text{W}}(h) + c_{\text{G}}\mathcal{P}_{\text{G}}(h) + c_{\text{C}}\mathcal{P}_{\text{C}}(h) + c_{\text{T}}\mathcal{P}_{\text{T}}(h) + c_{\text{H}}\mathcal{P}_{\text{H}}(h) + c_{\Box}\mathcal{P}_{\Box}(h)] \\ &+ \xi\sum_{i=1}^{10} c_i\mathcal{P}_i(h) + \xi^2\sum_{i=11}^{25} c_i\mathcal{P}_i + \xi^4 c_{26}\mathcal{P}_{26} + \cdots\end{aligned}$$

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

ξ 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.

Chiral Expansion II

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

$$\Delta\mathcal{L} = \xi[c_{\rm B}\mathcal{P}_{\rm B}(h) + c_{\rm W}\mathcal{P}_{\rm W}(h) + c_{\rm G}\mathcal{P}_{\rm G}(h) + c_{\rm H}\mathcal{P}_{\rm H}(h) + c_{\rm C}\mathcal{P}_{\rm C}(h) + c_{\rm T}\mathcal{P}_{\rm T}(h) + c_1\mathcal{P}_1(h) + c_2\mathcal{P}_2(h) + c_3\mathcal{P}_3(h) + c_4\mathcal{P}_4(h) + c_5\mathcal{P}_5(h)]$$

The above operators take the form:

$$\mathcal{P}_{\rm B}(h) = -\frac{g'^2}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_{\rm B}(h) \qquad \mathcal{P}_{\rm W}(h) = -\frac{g'^2}{4}W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_{\rm W}(h)$$
$$\mathcal{P}_{\rm G}(h) = -\frac{g'^2}{4}G^a_{\mu\nu}G^{a\mu\nu}\mathcal{F}_G(h) \qquad \mathcal{P}_{\rm H}(h) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\mathcal{F}_H(h)$$
$$\mathcal{P}_{\rm C}(h) = -\frac{v^2}{4}Tr(\mathbf{V}^\mu\mathbf{V}_\mu)\mathcal{F}_C(h) \qquad \mathcal{P}_{\rm T}(h) = \frac{v^2}{4}Tr(\mathbf{T}\mathbf{V}_\mu)Tr(\mathbf{T}\mathbf{V}^\mu)\mathcal{F}_T(h)$$
$$\mathcal{P}_1(h) = gg'B_{\mu\nu}Tr(\mathbf{T}W^{\mu\nu})\mathcal{F}_1(h) \qquad \mathcal{P}_2(h) = ig'B_{\mu\nu}Tr(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2(h)$$
$$\mathcal{P}_3(h) = igTr(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2(h) \qquad \mathcal{P}_4(h) = ig'B_{\mu\nu}Tr(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4(h)$$
$$\mathcal{P}_5(h) = igTr(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5(h)$$

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu\mathbf{U})\mathbf{U}^\dagger \quad T \equiv \mathbf{U}\sigma_3\mathbf{U}^\dagger \qquad \mathbf{U}(x) \to L\mathbf{U}(x)R^\dagger \quad \mathbf{U}(x) = \exp(i\sigma_a\pi^a(x)/v)$$

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 $SU(2)$ $a_i = b_i = c_i$

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(Very) Brief Comparison of Bases

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

For small ξ we can relate the Linear basis to the Chiral (more operators):

$$
\begin{array}{lllllll}
\mathcal{O}_{\rm WW} & = & \frac{g^2}{4}\Phi^\dagger W^{\mu\nu}W_{\mu\nu}\Phi & \longrightarrow & \mathcal{P}_{\rm W} & = & -\frac{g^2}{2}Tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu})\mathcal{F}_{\rm W}(h) \\
\mathcal{O}_{\rm BB} & = & \frac{g'^2}{4}\Phi^\dagger B^{\mu\nu}B_{\mu\nu}\Phi & \longrightarrow & \mathcal{P}_{\rm B} & = & -\frac{g'^2}{4}Tr(B_{\mu\nu}B^{\mu\nu})\mathcal{F}_{\rm B}(h) \\
\mathcal{O}_{\rm BW} & = & \frac{gg'}{4}\Phi^\dagger B^{\mu\nu}W_{\mu\nu}\Phi & \longrightarrow & \mathcal{P}_1 & = & gg'B_{\mu\nu}Tr(\mathbf{T}W^{\mu\nu})\mathcal{F}_1 \\
\mathcal{O}_{\rm B} & = & \frac{g'}{2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) & \longrightarrow & \mathcal{P}_2 & = & ig'B_{\mu\nu}Tr(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2(h) \\
 & & & \longrightarrow & \mathcal{P}_4 & = & ig'B_{\mu\nu}Tr(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4(h) \\
\mathcal{O}_{\rm W} & = & \frac{g}{2}(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) & \longrightarrow & \mathcal{P}_3 & = & igTr(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3(h) \\
 & & & \longrightarrow & \mathcal{P}_5 & = & igTr(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5(h) \\
\mathcal{O}_{\phi,1} & = & (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D_\nu\Phi) & \longrightarrow & \mathcal{P}_{\rm T} & = & \frac{v^2}{4}Tr(\mathbf{T}\mathbf{V}_\mu)Tr(\mathbf{T}\mathbf{V}^\mu)\mathcal{F}_{\rm T}(h) \\
\mathcal{O}_{\phi,2} & = & \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi) & \longrightarrow & \mathcal{P}_{\rm H} & = & \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\mathcal{F}_{\rm H}(h) \\
\mathcal{O}_{\phi,4} & = & (D_\mu\Phi)^\dagger(D_\nu\Phi)(\Phi^\dagger\Phi) & \longrightarrow & \mathcal{P}_{\rm C} & = & -\frac{v^2}{4}Tr(\mathbf{V}_\mu\mathbf{V}^\mu)\mathcal{F}_{\rm C}
\end{array}
$$

(Very) Brief Comparison of Bases II

Each operator contributes to particular HVV and TGV vertices.
In particular[3]:

	$\mathcal{O}_{\rm BB}$	$\mathcal{O}_{\rm WW}$	$\mathcal{O}_{\rm B}$	$\mathcal{O}_{\rm W}$	$\mathcal{P}_{\rm B}$	$\mathcal{P}_{\rm W}$	$\mathcal{P}_2$	$\mathcal{P}_4$	$\mathcal{P}_3$	$\mathcal{P}_5$
$h\gamma\gamma$	✘	✘			✘	✘				
$h\gamma Z$	✘	✘	✘	✘	✘	✘		✘		✘
hZZ	✘	✘	✘	✘	✘	✘		✘		✘
HW^+W^-		✘		✘		✘				✘
γW^+W^-			✘	✘			✘		✘	
ZW^+W^-			✘	✘			✘		✘	

Notice that green illustrates the decorrelation of TGV from Higgs data for

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

And blue illustrates a similar decorrelation for

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

[3] $\mathcal{O}_{\phi 4,\phi 2}$ ($\mathcal{P}_{H,T}$) give shifts to all SM HVV & Hff vertices

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$h\gamma\gamma$	✗	✗			✗	✗				
$h\gamma Z$	✗	✗	✗	✗	✗	✗		✗		✗
hZZ	✗	✗	✗	✗	✗	✗		✗		✗
HW^+W^-		✗		✗		✗				✗
γW^+W^-			✗	✗			✗		✗	
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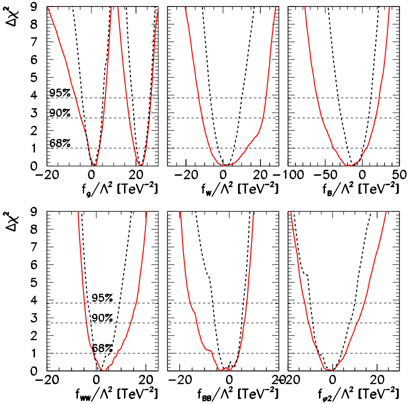
Higgs Phenomenology in Linear Expansion

Constructing a χ^2 fit to the data from LHC and TeVatron for the operators,

$$\{\mathcal{O}_{\rm GG} \quad \mathcal{O}_{\rm WW} \quad \mathcal{O}_{\rm BB} \quad \mathcal{O}_{\rm W} \quad \mathcal{O}_{\rm B} \quad \mathcal{O}_{\phi,2}\}$$

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 $\frac{f_g}{\Lambda^2} \sim -2$SM-loop

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

TGV$\to$direct effect on f_W & f_B

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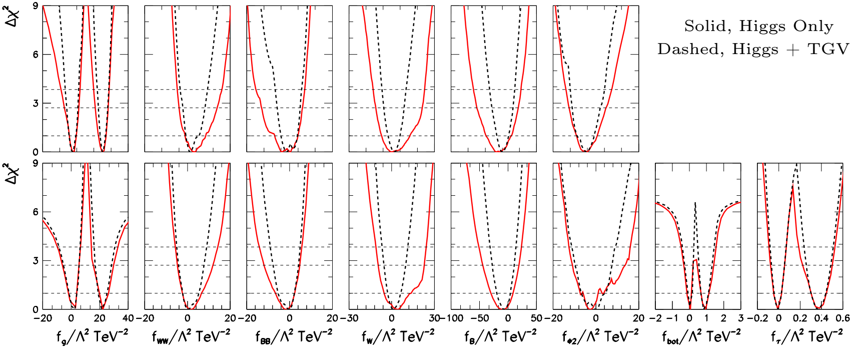

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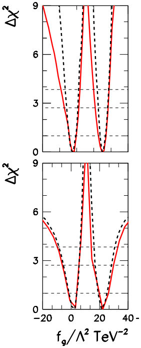
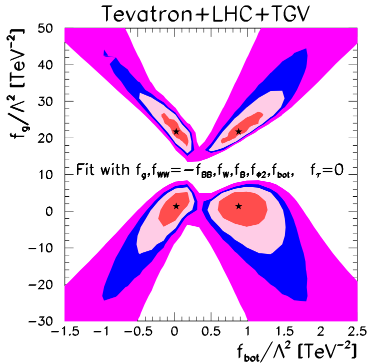
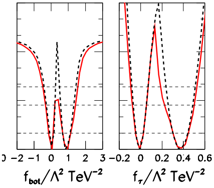




Solid, Higgs Only
Dashed, Higgs + TGV(LEP)



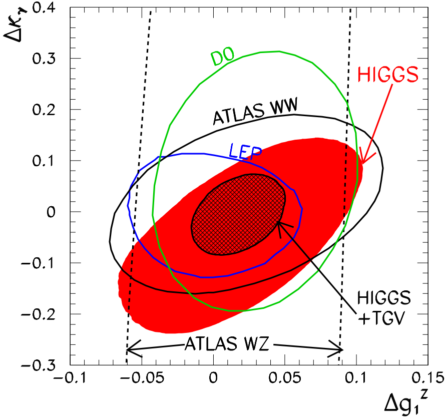
Higgs Phenomenology in Linear Expansion II

	Fit with $f_{bot} = f_\tau = 0$		Fit with f_{bot} and f_τ	
	Best fit	90% CL allowed range	Best fit	90% CL allowed range
f_g/Λ^2 (TeV^{-2})	1.1, 22	$[-3.3, 5.1] \cup [19, 26]$	2.7, 21	$[-5.3, 5.8] \cup [17, 22]$
f_{WW}/Λ^2 (TeV^{-2})	1.5	$[-3.2, 8.2]$	0.37	$[-4.2, 7.7]$
f_{BB}/Λ^2 (TeV^{-2})	-1.6	$[-7.5, 5.3]$	-0.37	$[-7.7, 4.2]$
f_W/Λ^2 (TeV^{-2})	2.1	$[-5.6, 9.6]$	1.0	$[-5.4, 9.8]$
f_B/Λ^2 (TeV^{-2})	-10	$[-29, 8.9]$	-7.0	$[-28, 11]$
$f_{\phi,2}/\Lambda^2$ (TeV^{-2})	-1.0	$[-10, 8.5]$	-0.58	$[-9.8, 7.5]$
f_{bot}/Λ^2 (TeV^{-2})	—–	—–	0.01, 0.83	$[-0.28, 0.24] \cup [0.55, 1.3]$
f_τ/Λ^2 (TeV^{-2})	—–	—–	-0.01, 0.37	$[-0.07, 0.05] \cup [0.26, 0.49]$

- 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,



$$\Delta g_1^Z = g_1^Z - 1 = \frac{g^2 v^2}{8 c_W^2 \Lambda^2} f_{\rm W}$$

$$\Delta\kappa_\gamma = \kappa_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2}(f_{\rm W} + f_{\rm B})$$

$$\Delta\kappa_Z = \kappa_Z - 1 = \frac{g^2 v^2}{8 c_W^2 \Lambda^2}(c_W^2 f_{\rm W} - s_W^2 f_{\rm B})$$

Where,

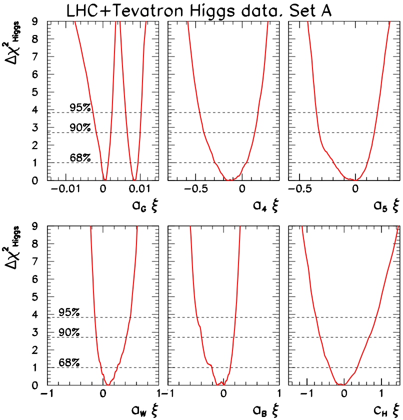
$$\mathcal{L}_{WWV} = -i g_{WWV}\left\{ g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^{-\,\nu\rho} V_\rho{}^\mu \right\}$$

Higgs Phenomenology in Chiral Realization

A similar χ^2 fit for the Chiral operators,

$$\mathcal{P}_G \quad \mathcal{P}_4 \quad \mathcal{P}_5 \quad \mathcal{P}_B \quad \mathcal{P}_W \quad \mathcal{P}_H$$

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 $\mathcal{O}_\mathrm{B}$ and $\mathcal{P}_2, \mathcal{P}_4$ and $\mathcal{O}_\mathrm{W}$ and $\mathcal{P}_3, \mathcal{P}_5$:

$$\mathcal{O}_\mathrm{B} = \tfrac{v^2}{16}\mathcal{P}_2 + \tfrac{v^2}{8}\mathcal{P}_4 \quad \mathcal{O}_\mathrm{W} = \tfrac{v^2}{8}\mathcal{P}_3 - \tfrac{v^2}{4}\mathcal{P}_5$$

We define the discriminating quantities (using a similar relation for $\mathcal{O}_W$ and $\mathcal{P}_3, \mathcal{P}_5$):

$$\begin{array}{lll} \Sigma_\mathrm{B} \equiv 4(2c_2 + a_4) & \Sigma_\mathrm{W} \equiv 2(2c_3 - a5), & \Sigma_\mathrm{B(W)} \rightarrow \frac{f_\mathrm{B(W)} v^2}{\Lambda^2} \\ \Delta_\mathrm{B} \equiv 4(2c_2 - a4) & \Delta_\mathrm{W} \equiv 2(2c_3 + a5), & \Delta_\mathrm{B} = \Delta_\mathrm{W} \rightarrow 0 \end{array} \quad \text{(Linear limit)}$$

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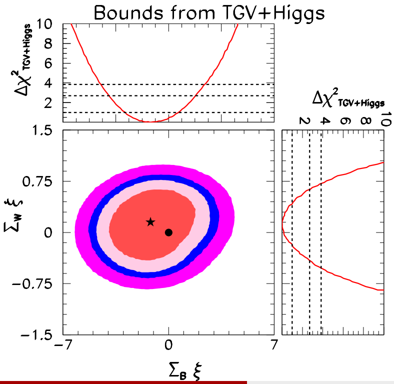
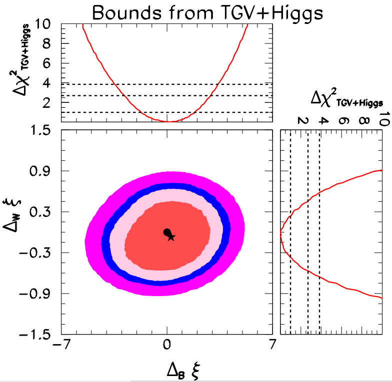
We define the discriminating quantities (using a similar relation for $\mathcal{O}_W$ and $\mathcal{P}_3, \mathcal{P}_5$):

$$\Sigma_{\rm B} \equiv 4(2c_2 + a_4) \quad \Sigma_{\rm W} \equiv 2(2c_3 - a5), \quad \Sigma_{\rm B(W)} \to \frac{f_{\rm B(W)} v^2}{\Lambda^2}$$
$$\Delta_{\rm B} \equiv 4(2c_2 - a4) \quad \Delta_{\rm W} \equiv 2(2c_3 + a5), \quad \Delta_{\rm B} = \Delta_{\rm W} \to 0$$

(Linear limit)





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.

Backup: Data Points