Effective field theories vs. oblique parameters in precision electroweak analyses

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based on 1510.08462, 1512.03056 w/ James Wells

Invitation: misconceptions about EFT & oblique parameters

- Oblique parameters S, T etc. can be used to constrain any (calculable) BSM theory. X

- Oblique parameters S, T etc. can be used to constrain the general dimension-6 EFT parameter space. X

- Oblique parameters S, T, etc. can be used to constrain "universal theories," where *only bosonic operators* appear in the EFT Lagrangian, *no matter which basis is used*. X

Introduction

EFT & oblique parameters

Effective field theory (EFT)

- General, model-independent and consistent approach to precision analyses, in search of deviations from the Standard Model (SM).

dimension-6 operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i c_i \frac{\mathcal{O}_i}{v^2} + \dots \quad \text{where} \quad c_i \sim \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$$

Λ ~ TeV?

- Theory prediction for observables

$$\hat{\mathcal{O}}^{\text{SMEFT}} = \hat{\mathcal{O}}^{\text{SM}}\left(1 + \bar{\delta}^{\text{NP}}\hat{\mathcal{O}}\right) \quad \text{where} \quad \bar{\delta}^{\text{NP}}\hat{\mathcal{O}} = \sum_i a_i c_i + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$$

~ O(1%)?

Wells, ZZ, 1406.6070

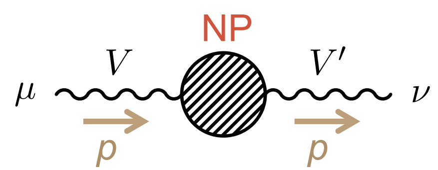
- Compare with precision data ➔ constrain/determine c_i ➔ infer UV theory.

EFT operator bases

- To use EFT consistently, we need a complete, non-redundant operator basis.
  - **Warsaw basis**
    - Buchmuller and Wyler (1986)
    - **Grzadkowski, Iskrzynski, Misiak, Rosiek (1008.4884)**
  - **SILH basis**
    - Giudice, Grojean, Pomarol, Rattazzi (hep-ph/0703164)
    - Contino, Ghezzi, Grojean, Muhlleitner, Spira (1303.3876)
    - **Elias-Miro, Espinosa, Masso, Pomarol (1308.1879)**
  - **EGGM basis**
    - Elias-Miro, Espinosa, Masso, Pomarol (1302.5661)
    - **Elias-Miro, Grojean, Gupta, Marzocca (1312.2928)**
- They are equivalent descriptions of the theory, related by field redefinitions (equivalently, SM equations of motion).

Oblique parameters S, T, etc.

- Parameterization of vector boson self-energy corrections.
  - Initiated by Kennedy and Lynn (1989).
  - S, T, U proposed by Peskin and Takeuchi (1992).
  - Extended by Maksymyk, Burgess, London (hep-ph/9306267), Barbieri, Pomarol, Rattazzi, Strumia (hep-ph/0405040), etc.



$$\Pi^{\mu\nu}_{VV'}(p) = \Big(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\Big)\Pi_{VV'}(p^2) + \frac{p^\mu p^\nu}{p^2}(\dots)$$ (new physics part only)

$$\text{where} \quad \Pi_{VV'}(p^2) = \Pi_{VV'}(0) + \Pi'_{VV'}(0)p^2 + \frac{1}{2}\Pi''_{VV'}(0)(p^2)^2 + \dots$$

$$\Rightarrow \quad \hat{S} \equiv \tfrac{\alpha}{4s_\theta^2} S \equiv -\tfrac{c_\theta}{s_\theta}\Pi'_{3B}(0), \quad \hat{T} \equiv \alpha T \equiv \tfrac{1}{m_W^2}\big[\Pi_{WW}(0) - \Pi_{33}(0)\big], \ \text{etc.}$$

- See e.g. PDG for current constraints on S and T from precision EW data.

Oblique parameters: caveats

$$\hat{S} \equiv \frac{\alpha}{4s_\theta^2} S \equiv -\frac{c_\theta}{s_\theta} \Pi'_{3B}(0), \quad \hat{T} \equiv \alpha T \equiv \frac{1}{m_W^2} \big[\Pi_{WW}(0) - \Pi_{33}(0)\big], \text{ etc.}$$

- 1) $\Pi_{VV'}(p^2)$ are not invariant under field redefinitions.
  - They are NOT physical observables.
  - In the EFT, values of $\Pi_{VV'}(p^2)$ are basis-dependent and ambiguous.
    - *See Sanchez-Colon and Wudka (hep-ph/9805366), Grojean, Skiba, Terning (hep-ph/0602154), Trott (1409.7605) for earlier discussions.*

- 2) Bounds on S, T, etc. are derived assuming they capture all the BSM effects (or at least the dominant ones) on the processes under study [e.g. "no Zff vertex corrections"].
  - This assumption is NOT satisfied for the most *general* BSM deformations.
  - Thus S, T, etc. are meaningful ONLY when restrictions are imposed.
  - Generally speaking, these restrictions define universal theories.

Consistent EFT description of universal theories

based on 1510.08462

EFT definition of universal theories

- Universal theories are theories for which, by field redefinitions, it is possible to write the effective Lagrangian as $\boxed{\mathcal{L}_{\text{universal}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{16} c_i \frac{\mathcal{O}_i^{\text{bosonic}}}{v^2}}$

$c_i \sim \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$

$$\mathcal{O}_W \xleftrightarrow{\text{IBP}} \mathcal{O}_{HW} + \frac{1}{4}(\mathcal{O}_{WW} + \mathcal{O}_{WB}),$$
$$\mathcal{O}_B \xleftrightarrow{\text{IBP}} \mathcal{O}_{HB} + \frac{1}{4}(\mathcal{O}_{BB} + \mathcal{O}_{WB}),$$

5 independent among the 7 above dashed line

	Operator	Warsaw	EGGM	SILH
1	$\mathcal{O}_W = \frac{ig}{2}(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H)D^\nu W^a_{\mu\nu}$	$\times$		
2	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu}$	$\times$		
3	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$\times$	$\times$	
4	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\times$	$\times$	
5	$\mathcal{O}_{WW} = g^2\lvert H\rvert^2 W^a_{\mu\nu}W^{a\mu\nu}$	$Q_{HW} = \lvert H\rvert^2 W^a_{\mu\nu}W^{a\mu\nu}$		$\times$
6	$\mathcal{O}_{WB} = gg'H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$	$Q_{HWB} = H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$		$\times$
7	$\mathcal{O}_{BB} = g'^2\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$Q_{HB} = \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$		
8	$\mathcal{O}_{GG} = g_s^2\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$Q_{HG} = \lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$		
9	$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	$\times$		$\times$
10	$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$	$\times$		$\times$
11	$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$	$\times$		$\times$
12	$\mathcal{O}_{3W} = \frac{g}{6}\epsilon^{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$	$Q_W = \epsilon^{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$		
13	$\mathcal{O}_{3G} = \frac{g_s}{6}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$Q_G = f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$		
14	$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$Q_{HD} = \lvert H^\dagger D_\mu H\rvert^2$		
15	$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$	$Q_{H\Box} = \lvert H\rvert^2\Box\lvert H\rvert^2$		
16	$\mathcal{O}_6 = \lambda\lvert H\rvert^6$	$Q_H = \lvert H\rvert^6$		
17	$\mathcal{O}_r = \lvert H\rvert^2\lvert D_\mu H\rvert^2$	$\times$	$\times$	$\times$
18	$\mathcal{O}_{K4} = \lvert D^2 H\rvert^2$	$\times$	$\times$	$\times$

- 16 independent CP-even bosonic operators one can possibly write down.
- The most general dim-6 deformations of the SM in the bosonic sector.

Translating $\boxed{\mathcal{L}_{\text{universal}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{16} c_i \frac{\mathcal{O}_i^{\text{bosonic}}}{v^2}}$ into the Warsaw basis

- 7 of the 16 bosonic operators do not appear in Warsaw basis.
- Their effects are captured elsewhere.
- Example:

$$ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \xrightarrow{\text{IBP}} -\frac{gg'}{4}H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu} + \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu} - \frac{g'^2}{4}|H|^2 B_{\mu\nu}B^{\mu\nu}$$

$$\xrightarrow{\text{EoM}} -\frac{gg'}{4}H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu} - \frac{g'^2}{4}(H^\dagger \overleftrightarrow{D}_\mu H)^2 - \frac{g'^2}{4}|H|^2 B_{\mu\nu}B^{\mu\nu}$$

$$\boxed{+\frac{ig'^2}{2}\sum_f Y_f (H^\dagger \overleftrightarrow{D}_\mu H)\bar{f}\gamma^\mu f}$$

$$\partial^\nu B_{\mu\nu} = \frac{ig'}{2}H^\dagger \overleftrightarrow{D}_\mu H + g'\sum_f Y_f \bar{f}\gamma_\mu f$$

  - LHS: bosonic operator (absent in Warsaw basis).
  - RHS: other bosonic operators, plus fermionic operator combination (present in Warsaw basis).
  - "No Zff vertex corrections" = "universal Zff vertex corrections".

Translating $\boxed{\mathcal{L}_{\text{universal}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{16} c_i \frac{\mathcal{O}_i^{\text{bosonic}}}{v^2}}$ into the Warsaw basis

$$\begin{aligned}\mathcal{L}_{\text{universal}} = \mathcal{L}_{\text{SM}} + \frac{1}{v^2}\big(&C_{HW}Q_{HW} + C_{HB}Q_{HB} + C_{HG}Q_{HG} + C_{HWB}Q_{HWB} + C_W Q_W \\ &+C_G Q_G + C_{HD}Q_{HD} + C_{H\Box}Q_{H\Box} + C_H Q_H + C_{HJW}Q_{HJW} + C_{HJB}Q_{HJB} \\ &+C_{2JW}Q_{2JW} + C_{2JB}Q_{2JB} + C_{2JG}Q_{2JG} + C_y Q_y + C_{2y}Q_{2y}\big),\end{aligned} \tag{2.1}$$

9 bosonic operators

7 fermionic operator combinations (effects equivalent to the other 7 independent bosonic operators)

Definition	Warsaw basis operator combination
$Q_{HJW} \equiv \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) J_W^{a\mu}$	$\frac{1}{4}g^2\big([Q^{(3)}_{Hq}]_{ii} + [Q^{(3)}_{Hl}]_{ii}\big)$
$Q_{HJB} \equiv \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H) J_B^{\mu}$	$\frac{1}{2}g'^2\big(Y_q[Q^{(1)}_{Hq}]_{ii} + Y_l[Q^{(1)}_{Hl}]_{ii}$ $+Y_u[Q_{Hu}]_{ii} + Y_d[Q_{Hd}]_{ii} + Y_e[Q_{He}]_{ii}\big)$
$Q_{2JW} \equiv J^a_{W\mu} J_W^{a\mu}$	$g^2\big(\frac{1}{4}[Q^{(3)}_{qq}]_{iijj} - \frac{1}{4}[Q_{ll}]_{iijj} + \frac{1}{2}[Q_{ll}]_{ijji} + \frac{1}{2}[Q^{(3)}_{lq}]_{iijj}\big)$
$Q_{2JB} \equiv J_{B\mu} J_B^{\mu}$	$g'^2\big(Y_q^2[Q^{(1)}_{qq}]_{iijj} + Y_l^2[Q_{ll}]_{iijj} + 2Y_qY_l[Q^{(1)}_{lq}]_{iijj}$ $+Y_u^2[Q_{uu}]_{iijj} + Y_d^2[Q_{dd}]_{iijj} + Y_e^2[Q_{ee}]_{iijj}$ $+2Y_qY_u[Q^{(1)}_{qu}]_{iijj} + 2Y_qY_d[Q^{(1)}_{qd}]_{iijj} + 2Y_qY_e[Q_{qe}]_{iijj}$ $+2Y_lY_u[Q_{lu}]_{iijj} + 2Y_lY_d[Q_{ld}]_{iijj} + 2Y_lY_e[Q_{le}]_{iijj}$ $+2Y_uY_d[Q^{(1)}_{ud}]_{iijj} + 2Y_uY_e[Q_{eu}]_{iijj} + 2Y_dY_e[Q_{ed}]_{iijj}\big)$
$Q_{2JG} \equiv J^A_{G\mu} J_G^{A\mu}$	$g_s^2\big(-\frac{1}{6}[Q^{(1)}_{qq}]_{iijj} + \frac{1}{4}[Q^{(1)}_{qq}]_{ijji} + \frac{1}{4}[Q^{(3)}_{qq}]_{ijji}$ $-\frac{1}{6}[Q_{uu}]_{iijj} + \frac{1}{2}[Q_{uu}]_{ijji} - \frac{1}{6}[Q_{dd}]_{iijj} + \frac{1}{2}[Q_{dd}]_{ijji}$ $+2[Q^{(8)}_{qu}]_{iijj} + 2[Q^{(8)}_{qd}]_{iijj} + 2[Q^{(8)}_{ud}]_{iijj}\big)$
$Q_y \equiv \lvert H\rvert^2(H_\alpha J_y^\alpha + \text{h.c.})$	$[y_u]_{ij}[Q_{uH}]_{ij} + [V_{\text{CKM}}y_d]_{ij}[Q_{dH}]_{ij} + [y_e]_{ij}[Q_{eH}]_{ij} + \text{h.c.}$
$Q_{2y} \equiv J^\dagger_{y\alpha} J_y^{\alpha}$	$-[y_u]_{il}[y_u^\dagger]_{kj}\big(\frac{1}{6}[Q^{(1)}_{qu}]_{ijkl} + [Q^{(8)}_{qu}]_{ijkl}\big) - \frac{1}{2}[y_e]_{il}[y_e^\dagger]_{kj}[Q_{le}]_{ijkl}$ $-[V_{\text{CKM}}y_d]_{il}[y_d^\dagger V^\dagger_{\text{CKM}}]_{kj}\big(\frac{1}{6}[Q^{(1)}_{qd}]_{ijkl} + [Q^{(8)}_{qd}]_{ijkl}\big)$ $+\big([y_u]_{ij}[V_{\text{CKM}}y_d]_{kl}[Q^{(1)}_{quqd}]_{ijkl} - [y_e]_{ij}[y_u]_{kl}[Q^{(1)}_{lequ}]_{ijkl}$ $+[y_e]_{ij}[y_d^\dagger V^\dagger_{\text{CKM}}]_{kl}[Q_{ledq}]_{ijkl} + \text{h.c.}\big)$

Still 16-dimensional parameter space (subspace of full SMEFT).

Oblique parameters in universal theories

- To unambiguously define oblique parameters from $\Pi_{VV'}(p^2)$, we require the following 3 oblique parameters defining conditions be satisfied:
  - 1) The Lagrangian is written s.t. only bosonic operators are present.
  - 2) The kinetic terms of $W^{\pm}$ and B are canonically normalized.
  - 3) $\Pi_{WW}(0) = 0$ where W represents $W^{\pm}$.

Barbieri, Pomarol, Rattazzi, Strumia, hep-ph/0405040

- 1) is possible only in universal theories, where field redefinitions can put the Lagrangian into the form $\mathcal{L}_{\text{SM}} + \sum_{i=1}^{16} c_i \frac{\mathcal{O}_i^{\text{bosonic}}}{v^2}$, no matter which basis one works with.

- 2) and 3) fix SM parameters g, g', v.

Oblique parameters in universal theories

- Up to dimension 6, the nonzero oblique parameters are:

$$\begin{aligned}
\hat{S} &\equiv \frac{\alpha}{4s_\theta^2} S \equiv -\frac{c_\theta}{s_\theta}\bar{\Pi}'_{3B}(0), \\
\hat{T} &\equiv \alpha T \equiv \frac{1}{m_W^2}\left[\bar{\Pi}_{WW}(0) - \bar{\Pi}_{33}(0)\right], \\
W &\equiv -\frac{m_W^2}{2}\bar{\Pi}''_{33}(0), \\
Y &\equiv -\frac{m_W^2}{2}\bar{\Pi}''_{BB}(0) \\
Z &\equiv -\frac{m_W^2}{2}\bar{\Pi}''_{GG}(0),
\end{aligned}$$

  - Their expressions in different bases are related by basis transformations.

	EGGM	SILH	Warsaw	$\mathrm{B_E}$	$\mathrm{B_S}$
$\hat{S}$	$g^2(E_{WB} + \frac{1}{4}E_W + \frac{1}{4}E_B)$	$g^2(\frac{1}{4}S_W + \frac{1}{4}S_B - \frac{1}{2}S_{2JW} - \frac{1}{2}S_{2JB})$	$g^2(\frac{1}{gg'}C_{HWB} + \frac{1}{4}C_{HJW} + \frac{1}{4}C_{HJB} - \frac{1}{2}C_{2JW} - \frac{1}{2}C_{2JB})$	$g^2(\bar{E}_{WB} + \frac{1}{4}\bar{E}_W + \frac{1}{4}\bar{E}_B)$	$g^2(\frac{1}{4}\bar{S}_W + \frac{1}{4}\bar{S}_B)$
$\hat{T}$	E_T	$S_T - \frac{g'^2}{2}S_{2JB}$	$-\frac{1}{2}C_{HD} + \frac{g'^2}{2}(C_{HJB} - C_{2JB})$	$\bar{E}_T$	$\bar{S}_T$
W	$\frac{g^2}{4}E_{2W}$	$-\frac{g^2}{2}S_{2JW}$	$-\frac{g^2}{2}C_{2JW}$	$\frac{g^2}{4}\bar{E}_{2W}$	$\frac{g^2}{4}\bar{S}_{2W}$
Y	$\frac{g^2}{4}E_{2B}$	$-\frac{g^2}{2}S_{2JB}$	$-\frac{g^2}{2}C_{2JB}$	$\frac{g^2}{4}\bar{E}_{2B}$	$\frac{g^2}{4}\bar{S}_{2B}$
Z	$\frac{g^2}{4}E_{2G}$	$-\frac{g^2}{2}S_{2JG}$	$-\frac{g^2}{2}C_{2JG}$	$\frac{g^2}{4}\bar{E}_{2G}$	$\frac{g^2}{4}\bar{S}_{2G}$

Coefficients of fermionic operator combinations appear!

See 1510.08462 for details.

Conclusions

- ~~Oblique parameters S, T etc. can be used to constrain any (calculable) BSM theory.~~
- Generally speaking, oblique parameters S, T, etc. can only be used to constrain universal theories.

- ~~Oblique parameters S, T etc. can be used to constrain the general dimension-6 EFT parameter space.~~
- They cannot be used to constrain the full EFT parameter space. Restrictions must be imposed.

Conclusions

- ~~Oblique parameters S, T, etc. can be used to constrain "universal theories," where *only bosonic operators* appear in the EFT Lagrangian, *no matter which basis is used*.~~
- Universal theories are defined by a 16-dimensional subspace of the full dimension-6 EFT parameter space. Fermionic operator combinations can appear in some bases (e.g. Warsaw).

- Final comment
  - Universal theories can flow to non-universal theories under RG.
  - At *EW scale*, it is not possible to write $\mathcal{L}_{\rm SM} + \sum_{i=1}^{16} c_i \frac{\mathcal{O}_i^{\rm bosonic}}{v^2}$ (unless w/ fine tuning). So *a priori*, oblique parameters are not well-defined.
  - See 1512.03056 for detailed discussion of RG effects.

Thank you!

The end

Backup slides

Example of ambiguity

adapted from Grojean, Skiba, Terning, hep-ph/0602154

- Field redefinition of $\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$ is equivalent to application of the SM equations of motion (EoM) on dimension-6 operators.

$$\phi \to \phi + \delta\phi \quad \Rightarrow \quad S[\phi]_{\mathrm{EFT}} \to S[\phi]_{\mathrm{EFT}} + \left(\frac{\delta S}{\delta\phi}\right)_{\mathrm{SM}} \delta\phi + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$$

SM EoM

$\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$

anomalous triple-gauge couplings

$$ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \xrightarrow{\mathrm{IBP}} -\frac{gg'}{4} H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu} + \frac{ig'}{2} (H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu} - \frac{g'^2}{4} |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\xrightarrow{\mathrm{EoM}} -\frac{gg'}{4} H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu} - \frac{g'^2}{4} (H^\dagger \overleftrightarrow{D}_\mu H)^2$$

vector boson self-energy corrections (S, T)

$$\partial^\nu B_{\mu\nu} = \frac{ig'}{2} H^\dagger \overleftrightarrow{D}_\mu H + g' \sum_f Y_f \bar{f} \gamma_\mu f$$

$$+\frac{ig'^2}{2} \sum_f Y_f (H^\dagger \overleftrightarrow{D}_\mu H) \bar{f} \gamma^\mu f$$

anomalous Zff couplings

$$-\frac{g'^2}{4} |H|^2 B_{\mu\nu} B^{\mu\nu}.$$

affects Higgs physics only

- Physical effects are equivalent (e.g. $e^+e^- \to W^+W^-$).

	Operator	Warsaw	EGGM	SILH	$\mathrm{B_E}$	$\mathrm{B_S}$
1	$\mathcal{O}_W = \frac{ig}{2}(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H)D^\nu W^a_{\mu\nu}$	$\times$				
2	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu}$	$\times$				
3	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$\times$	$\times$		$\times$	
4	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\times$	$\times$		$\times$	
5	$\mathcal{O}_{WW} = g^2\lvert H\rvert^2 W^a_{\mu\nu}W^{a\mu\nu}$	$Q_{HW} = \lvert H\rvert^2 W^a_{\mu\nu}W^{a\mu\nu}$		$\times$		$\times$
6	$\mathcal{O}_{WB} = gg'H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$	$Q_{HWB} = H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$		$\times$		$\times$
7	$\mathcal{O}_{BB} = g'^2\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$	$Q_{HB} = \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$				
8	$\mathcal{O}_{GG} = g_s^2\lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$	$Q_{HG} = \lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$				
9	$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	$\times$		$\times$		
10	$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$	$\times$		$\times$		
11	$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$	$\times$		$\times$		
12	$\mathcal{O}_{3W} = \frac{g}{6}\epsilon^{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$	$Q_W = \epsilon^{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$				
13	$\mathcal{O}_{3G} = \frac{g_s}{6}f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$Q_G = f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$				
14	$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$Q_{HD} = \lvert H^\dagger D_\mu H\rvert^2$				
15	$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$	$Q_{H\Box} = \lvert H\rvert^2\Box\lvert H\rvert^2$				
16	$\mathcal{O}_6 = \lambda\lvert H\rvert^6$	$Q_H = \lvert H\rvert^6$				
17	$\mathcal{O}_r = \lvert H\rvert^2\lvert D_\mu H\rvert^2$	$\times$	$\times$	$\times$		
18	$\mathcal{O}_{K4} = \lvert D^2 H\rvert^2$	$\times$	$\times$	$\times$		
1	$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	$Q^{(1)}_{Hl}$		$\times$	unspecified	
2	$\mathcal{O}^{(3)l}_L = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu\sigma^a l)$	$Q^{(3)}_{Hl}$	$\times$	$\times$		
3	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	Q_{He}	$\times$			
4	$\mathcal{O}^l_{LL} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	Q_{ll}	$\times$			
5	$\mathcal{O}^e_{RR} = (\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$	Q_{ee}	$\times$			
6	$\mathcal{O}^{(8)ud}_{RR} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$	$Q^{(8)}_{ud}$	$\times$			
	other 38 fermionic operators	kept in all 3 bases				

18+6+38=62

Table 1. List of CP-even dimension-6 operators (column 1) in the notation of [33]. There are 53 independent operators (for one fermion generation assuming baryon number conservation) among the 24 listed (18 bosonic and 6 fermionic, separated by the horizontal solid line) plus 38 unlisted (fermionic) operators, so 9 of them should be eliminated to form a complete SMEFT basis. The eliminated operators for each of the three recently-proposed bases, Warsaw [79], EGGM [40], and SILH [33], are marked by "×" (the eliminated fermionic operators refer to the first-generation ones).

Some UV completions of universal theories

- New states at the scale Λ only couple to the bosonic sector of the SM;

- SM fermions are weakly coupled to new states at Λ via vector and/or scalar currents appearing in the SM; Barbieri, Pomarol, Rattazzi, Strumia, hep-ph/0405040

SM currents

$$J^A_{G\mu} \equiv g_s \sum_{f\in\{q,u,d\}} \bar{f}\gamma_\mu T^A f \xrightarrow{\text{EoM}} D^\nu G^A_{\mu\nu},$$

$$J^a_{W\mu} \equiv g \sum_{f\in\{q,l\}} \bar{f}\gamma_\mu \frac{\sigma^a}{2} f \xrightarrow{\text{EoM}} D^\nu W^a_{\mu\nu} - \frac{ig}{2} H^\dagger \sigma^a \overleftrightarrow{D}_\mu H,$$

$$J_{B\mu} \equiv g' \sum_{f\in\{q,l,u,d,e\}} Y_f \bar{f}\gamma_\mu f \xrightarrow{\text{EoM}} \partial^\nu B_{\mu\nu} - \frac{ig'}{2} H^\dagger \overleftrightarrow{D}_\mu H,$$

$$J^\alpha_y \equiv \bar{u} y_u^\dagger q_\beta \epsilon^{\beta\alpha} + \bar{q}^\alpha V_{\text{CKM}} y_d d + \bar{l}^\alpha y_e e$$
$$\xrightarrow{\text{EoM}} -(D^2 H^\dagger)^\alpha + \lambda v^2 H^{\dagger\alpha} - 2\lambda |H|^2 H^{\dagger\alpha},$$

bosonic fields

- etc.

  - Note: EFT definition of universal theories does not rely on UV completions.

Complete LO characterization of universal theories

- Generalizing the oblique parameters framework, we define 16 universal parameters, which completely characterize the 16-dimensional parameter space of the universal theories EFT:
  - 5 oblique parameters $\hat{S}$, $\hat{T}$, W, Y, Z;
  - 4 anomalous TGC parameters $\Delta\bar{g}_1^Z$, $\Delta\bar{\kappa}_\gamma$, $\bar{\lambda}_\gamma$, $\bar{\lambda}_g$;
  - 3 parameters for the rescaling of the SM h^3, hff, hVV couplings $\Delta\kappa_3$, $\Delta\bar{\kappa}_F$, $\Delta\bar{\kappa}_V$;
  - 3 parameters for the hVV couplings with non-SM Lorentz structures f_{gg}, $f_{z\gamma}$, $f_{\gamma\gamma}$;
  - 1 parameter for the $\mathcal{O}(y_f^2)$ four-fermion coupling c_{2y}.
- Their values are basis-independent for any specific universal theory.
  - See 1510.08462 for their expressions in different bases, and example applications.

Universal parameters from the effective Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\text{universal}} = & \left(\frac{\bar{g}\bar{v}}{2}\right)^2 \bar{W}^+_\mu \bar{W}^{-\mu} + (1-\underline{\hat{T}})\frac{1}{2}\left(\frac{\bar{g}\bar{v}}{2\bar{c}_\theta}\right)^2 \bar{Z}_\mu \bar{Z}^\mu \\
& -\frac{1}{2}\bar{G}^A_\mu \hat{K}^{\mu\nu}\bar{G}^A_\nu - \bar{W}^+_\mu \hat{K}^{\mu\nu}\bar{W}^-_\nu - \frac{1}{2}\bar{W}^3_\mu \hat{K}^{\mu\nu}\bar{W}^3_\nu - \underline{\hat{S}}\frac{\bar{s}_\theta}{\bar{c}_\theta}\bar{W}^3_\mu \hat{K}^{\mu\nu}\bar{B}_\nu - \frac{1}{2}\bar{B}_\mu \hat{K}^{\mu\nu}\bar{B}_\nu \\
& -\frac{1}{m_W^2}\left[\underline{Z}\frac{1}{2}\bar{G}^A_\mu \hat{K}^{2\mu\nu}\bar{G}^A_\nu + \underline{W}\left(\bar{W}^+_\mu \hat{K}^{2\mu\nu}\bar{W}^-_\nu + \frac{1}{2}\bar{W}^3_\mu \hat{K}^{2\mu\nu}\bar{W}^3_\nu\right) + \underline{Y}\frac{1}{2}\bar{B}_\mu \hat{K}^{2\mu\nu}\bar{B}_\nu\right] \\
& +i\bar{g}\Big\{(\bar{W}^+_{\mu\nu}\bar{W}^{-\mu} - \bar{W}^-_{\mu\nu}\bar{W}^{+\mu})\left[(1+\underline{\Delta\bar{g}^Z_1})\bar{c}_\theta \bar{Z}^\nu + \bar{s}_\theta \bar{A}^\nu\right] \\
& \quad +\frac{1}{2}\bar{W}^+_{[\mu,}\bar{W}^-_{\nu]}\left[(1+\underline{\Delta\bar{\kappa}_Z})\bar{c}_\theta \bar{Z}^{\mu\nu} + (1+\underline{\Delta\bar{\kappa}_\gamma})\bar{s}_\theta \bar{A}^{\mu\nu}\right] \\
& \quad +\frac{\underline{\bar{\lambda}_\gamma}}{m_W^2}\bar{W}^{+\nu}_\mu \bar{W}^{-\rho}_\nu(\bar{c}_\theta \bar{Z}_\rho{}^\mu + \bar{s}_\theta \bar{A}_\rho{}^\mu)\Big\} + \frac{W}{m_W^2}\hat{K}\circ\mathcal{L}^{\text{SM}}_{\bar{W}\bar{W}\bar{V}} \\
& \quad +\mathcal{L}^{\text{SM}}_{\bar{G}^3} - \frac{\underline{\bar{\lambda}_g}}{m_W^2}\frac{\bar{g}_s}{6}f^{ABC}\bar{G}^{A\nu}_\mu \bar{G}^{B\rho}_\nu \bar{G}^{C\mu}_\rho + \frac{Z}{m_W^2}\hat{K}\circ\mathcal{L}^{\text{SM}}_{\bar{G}^3} \\
& +\frac{1}{2}\partial_\mu \bar{h}\partial^\mu \bar{h} - \frac{1}{2}(2\bar{\lambda}\bar{v}^2)\bar{h}^2 - (1+\underline{\Delta\kappa_3})\bar{\lambda}\bar{v}\bar{h}^3 \\
& -\left[1 + (1+\underline{\Delta\bar{\kappa}_F})\frac{\bar{h}}{\bar{v}} + \left(\frac{3}{2}\Delta\bar{\kappa}_F - \frac{1}{2}\Delta\bar{\kappa}_V\right)\frac{\bar{h}^2}{\bar{v}^2}\right]\sum_{f'}\frac{\bar{y}_{f'}\bar{v}}{\sqrt{2}}\bar{f}'f' \\
& +(1+\underline{\Delta\bar{\kappa}_V})\frac{2\bar{h}}{\bar{v}}\left[\left(\frac{\bar{g}\bar{v}}{2}\right)^2 \bar{W}^+_\mu \bar{W}^{-\mu} + (1-2\hat{T})\frac{1}{2}\left(\frac{\bar{g}\bar{v}}{2\bar{c}_\theta}\right)^2 \bar{Z}_\mu \bar{Z}^\mu\right] \\
& \quad +(1+4\Delta\bar{\kappa}_V)\frac{\bar{h}^2}{\bar{v}^2}\left[\left(\frac{\bar{g}\bar{v}}{2}\right)^2 \bar{W}^+_\mu \bar{W}^{-\mu} + (1-6\hat{T})\frac{1}{2}\left(\frac{\bar{g}\bar{v}}{2\bar{c}_\theta}\right)^2 \bar{Z}_\mu \bar{Z}^\mu\right] \\
& +\left(\frac{\bar{h}}{\bar{v}} + \frac{\bar{h}^2}{2\bar{v}^2}\right)\left[\underline{f_{gg}}\frac{\bar{g}_s^2}{4}\partial_{[\mu,}\bar{G}^A_{\nu]}\partial^{[\mu,}\bar{G}^{A\nu]} + \underline{f_{ww}}\frac{\bar{g}^2}{2}\bar{W}^+_{\mu\nu}\bar{W}^{-\mu\nu} + \underline{f_{zz}}\frac{\bar{g}^2}{4\bar{c}_\theta^2}\bar{Z}_{\mu\nu}\bar{Z}^{\mu\nu}\right. \\
& \quad +\underline{f_{z\gamma}}\frac{\bar{g}\bar{g}'}{2}\bar{Z}_{\mu\nu}\bar{A}^{\mu\nu} + \underline{f_{\gamma\gamma}}\frac{\bar{e}^2}{4}\bar{A}_{\mu\nu}\bar{A}^{\mu\nu} + \underline{f_{w\Box}}\bar{g}^2(\bar{W}^-_\mu \partial_\nu \bar{W}^{+\mu\nu} + \text{h.c.}) \\
& \quad \left. +\underline{f_{z\Box}}\bar{g}^2\bar{Z}_\mu \partial_\nu \bar{Z}^{\mu\nu} + \underline{f_{\gamma\Box}}\bar{g}\bar{g}'\bar{Z}_\mu \partial_\nu \bar{A}^{\mu\nu}\right] \\
& +\underline{c_{2y}}J^\dagger_{y\alpha}J^\alpha_y + \sum_f i\bar{f}\gamma^\mu D_\mu f + \mathcal{O}(\bar{V}^4, \bar{h}^4, \bar{h}^3 f^2, \bar{h}^3\bar{V}^2, \bar{h}\bar{V}^3).
\end{aligned}
$$

$$
\begin{aligned}
\Delta\bar{\kappa}_Z &= \Delta\bar{g}^Z_1 - \frac{s_\theta^2}{c_\theta^2}\Delta\bar{\kappa}_\gamma, \\
f_{ww} &= f_{z\gamma} + s_\theta^2 f_{\gamma\gamma} + \frac{2}{g^2}\Delta\bar{\kappa}_\gamma, \\
f_{zz} &= (c_\theta^2 - s_\theta^2)f_{z\gamma} + c_\theta^2 s_\theta^2 f_{\gamma\gamma} + \frac{2}{g^2}\Delta\bar{\kappa}_\gamma, \\
f_{w\Box} &= -\frac{2c_\theta^2}{g^2}\Delta\bar{g}^Z_1, \\
f_{z\Box} &= -\frac{2}{g^2}\left[(c_\theta^2 - s_\theta^2)\Delta\bar{g}^Z_1 + \frac{s_\theta^2}{c_\theta^2}(\Delta\bar{\kappa}_\gamma - \hat{S})\right], \\
f_{\gamma\Box} &= -\frac{2}{g^2}(2c_\theta^2\Delta\bar{g}^Z_1 - \Delta\bar{\kappa}_\gamma + \hat{S}).
\end{aligned}
$$

Universal parameters in different bases

	EGGM	SILH	Warsaw	B_E	B_S
$\hat{S}$	$g^2(E_{WB} + \frac{1}{4}E_W + \frac{1}{4}E_B)$	$g^2(\frac{1}{4}S_W + \frac{1}{4}S_B - \frac{1}{2}S_{2JW} - \frac{1}{2}S_{2JB})$	$g^2(\frac{1}{gg'}C_{HWB} + \frac{1}{4}C_{HJW} + \frac{1}{4}C_{HJB} - \frac{1}{2}C_{2JW} - \frac{1}{2}C_{2JB})$	$g^2(\bar{E}_{WB} + \frac{1}{4}\bar{E}_W + \frac{1}{4}\bar{E}_B)$	$g^2(\frac{1}{4}\bar{S}_W + \frac{1}{4}\bar{S}_B)$
$\hat{T}$	E_T	$S_T - \frac{g'^2}{2}S_{2JB}$	$-\frac{1}{2}C_{HD} + \frac{g'^2}{2}(C_{HJB} - C_{2JB})$	$\bar{E}_T$	$\bar{S}_T$
W	$\frac{g^2}{4}E_{2W}$	$-\frac{g^2}{2}S_{2JW}$	$-\frac{g^2}{2}C_{2JW}$	$\frac{g^2}{4}\bar{E}_{2W}$	$\frac{g^2}{4}\bar{S}_{2W}$
Y	$\frac{g^2}{4}E_{2B}$	$-\frac{g^2}{2}S_{2JB}$	$-\frac{g^2}{2}C_{2JB}$	$\frac{g^2}{4}\bar{E}_{2B}$	$\frac{g^2}{4}\bar{S}_{2B}$
Z	$\frac{g^2}{4}E_{2G}$	$-\frac{g^2}{2}S_{2JG}$	$-\frac{g^2}{2}C_{2JG}$	$\frac{g^2}{4}\bar{E}_{2G}$	$\frac{g^2}{4}\bar{S}_{2G}$
$\Delta\bar{g}_1^Z$	$-\frac{g^2}{4c_\theta^2}E_W$	$-\frac{g^2}{4c_\theta^2}(S_W + S_{HW} - 2S_{2JW})$	$-\frac{g^2}{4c_\theta^2}(C_{HJW} - 2C_{2JW})$	$-\frac{g^2}{4c_\theta^2}\bar{E}_W$	$-\frac{g^2}{4c_\theta^2}(\bar{S}_W + \bar{S}_{HW})$
$\Delta\bar{\kappa}_\gamma$	g^2E_{WB}	$-\frac{g^2}{4}(S_{HW} + S_{HB})$	$\frac{c_\theta}{s_\theta}C_{HWB}$	$g^2\bar{E}_{WB}$	$-\frac{g^2}{4}(\bar{S}_{HW} + \bar{S}_{HB})$
$\bar{\lambda}_\gamma$	$-\frac{g^2}{4}E_{3W}$	$-\frac{g^2}{4}S_{3W}$	$-\frac{3g}{2}C_W$	$-\frac{g^2}{4}\bar{E}_{3W}$	$-\frac{g^2}{4}\bar{S}_{3W}$
$\bar{\lambda}_g$	$-\frac{g^2}{4}E_{3G}$	$-\frac{g^2}{4}S_{3G}$	$-\frac{3g^2}{2g_s}C_G$	$-\frac{g^2}{4}\bar{E}_{3G}$	$-\frac{g^2}{4}\bar{S}_{3G}$
$\Delta\kappa_3$	$-E_6 - \frac{3}{2}E_H$	$-S_6 - \frac{3}{2}S_H + \frac{g^2}{4}S_{2JW}$	$-\frac{1}{\lambda}C_H + 3C_{H\Box} - \frac{3}{4}C_{HD} - \frac{g^2}{4}(C_{HJW} - C_{2JW})$	$-\bar{E}_6 - \frac{3}{2}\bar{E}_H - \frac{1}{2}\bar{E}_r - 4\lambda\bar{E}_{K4}$	$-\bar{S}_6 - \frac{3}{2}\bar{S}_H - \frac{1}{2}\bar{S}_r - 4\lambda\bar{S}_{K4}$
$\Delta\bar{\kappa}_F$	$-E_y - \frac{1}{2}E_H$	$-S_y - \frac{1}{2}S_H + \frac{g^2}{4}S_{2JW}$	$-C_y + C_{H\Box} - \frac{1}{4}C_{HD} - \frac{g^2}{4}(C_{HJW} - C_{2JW})$	$-\frac{1}{2}\bar{E}_H - 2\lambda\bar{E}_{K4}$	$-\frac{1}{2}\bar{S}_H - 2\lambda\bar{S}_{K4}$
$\Delta\bar{\kappa}_V$	$-\frac{1}{2}E_H$	$-\frac{1}{2}S_H + \frac{3g^2}{4}S_{2JW}$	$C_{H\Box} - \frac{1}{4}C_{HD} - \frac{3g^2}{4}(C_{HJW} - C_{2JW})$	$-\frac{1}{2}(\bar{E}_H - \bar{E}_r)$	$-\frac{1}{2}(\bar{S}_H - \bar{S}_r)$
f_{gg}	$4E_{GG}$	$4S_{GG}$	$\frac{4}{g_s^2}C_{HG}$	$4\bar{E}_{GG}$	$4\bar{S}_{GG}$
$f_{z\gamma}$	$2[2c_\theta^2E_{WW} - 2s_\theta^2E_{BB} - (c_\theta^2 - s_\theta^2)E_{WB}]$	$-4s_\theta^2S_{BB} - \frac{1}{2}(S_{HW} - S_{HB})$	$\frac{2}{gg'}[2c_\theta s_\theta(C_{HW} - C_{HB}) - (c_\theta^2 - s_\theta^2)C_{HWB}]$	$2[2c_\theta^2\bar{E}_{WW} - 2s_\theta^2\bar{E}_{BB} - (c_\theta^2 - s_\theta^2)\bar{E}_{WB}]$	$-4s_\theta^2\bar{S}_{BB} - \frac{1}{2}(\bar{S}_{HW} - \bar{S}_{HB})$
$f_{\gamma\gamma}$	$4(E_{WW} + E_{BB} - E_{WB})$	$4S_{BB}$	$4(\frac{1}{g^2}C_{HW} + \frac{1}{g'^2}C_{HB} - \frac{1}{gg'}C_{HWB})$	$4(\bar{E}_{WW} + \bar{E}_{BB} - \bar{E}_{WB})$	$4\bar{S}_{BB}$
c_{2y}	E_{2y}	S_{2y}	C_{2y}	$\bar{E}_{K4}$	$\bar{S}_{K4}$

- These expressions are related by basis transformations.
- Values of universal parameters are basis-independent.

Universal vs. non-universal: EW sector

- In the general EFT,

"effective Vff couplings"

$$\mathcal{L}_{\rm CC} = \frac{\hat{g}}{\sqrt{2}}\Big\{\hat{W}^+_\mu\Big[\big(\delta_{ij}+\underline{[\delta g_L^{Wq}]_{ij}}\big)\bar{u}_{L,i}\gamma^\mu d_{L,j} + \big(\delta_{ij}+\underline{[\delta g_L^{Wl}]_{ij}}\big)\bar{\nu}_i\gamma^\mu e_{L,j}\Big] + \text{h.c.}\Big\},$$

$$\mathcal{L}_{\rm NC} = \sum_f\Big[\frac{\hat{e}}{\hat{c}_\theta\hat{s}_\theta}\hat{Z}_\mu\big((T^3_f - Q_f\hat{s}^2_\theta)\delta_{ij} + \underline{[\delta g^{Zf}_{L/R}]_{ij}}\big) + \hat{e}\hat{A}_\mu Q_f\delta_{ij}\Big]\bar{f}_i\gamma^\mu f_j,$$

Higgs basis, LHCHXSWG-INT-2015-001

  - Hatted fields are mass eigenstates.
  - Hatted parameters follow from redefinitions that undo new physics corrections of the input observables m_Z, G_F, α.

- In universal theories,

$[\delta g_L^{Wf}]_{ij}\ (f=q,l)$	$\delta_{ij}\Big(\frac{c_\theta^2}{c_\theta^2-s_\theta^2}\frac{\Delta\epsilon_1}{2} - \frac{s_\theta^2}{c_\theta^2-s_\theta^2}\Delta\epsilon_3\Big)$
$[\delta g_L^{Zf}]_{ij}\ (f=u_L,d_L,e_L,\nu)$	$\delta_{ij}\Big[T^3_f\frac{\Delta\epsilon_1}{2} + Q_f\frac{s_\theta^2}{c_\theta^2-s_\theta^2}\Big(\frac{\Delta\epsilon_1}{2}-\Delta\epsilon_3\Big)\Big]$
$[\delta g_R^{Zf}]_{ij}\ (f=u_R,d_R,e_R)$	$\delta_{ij}Q_f\frac{s_\theta^2}{c_\theta^2-s_\theta^2}\Big(\frac{\Delta\epsilon_1}{2}-\Delta\epsilon_3\Big)$

  - where $\Delta\epsilon_1 \equiv \hat{T} - W - \frac{s_\theta^2}{c_\theta^2}Y,\quad \Delta\epsilon_3 \equiv \hat{S} - W - Y.$

- Universal relations:

$$\boxed{\begin{array}{l}\delta g_L^{Wq} = \delta g_L^{Wl},\qquad \frac{\delta g_R^{Zu}}{Y_u} = \frac{\delta g_R^{Zd}}{Y_d} = \frac{\delta g_R^{Ze}}{Y_e},\\ \delta g_L^{Ze} + \delta g_L^{Z\nu} = \delta g_R^{Ze},\qquad \delta g_L^{Zu} + \delta g_L^{Zd} = \delta g_R^{Zu} + \delta g_R^{Zd},\end{array}}$$

Universal vs. non-universal: Yukawa sector

- In the general EFT,

$$\mathcal{L}_{hff} = -\frac{\hat{h}}{v} \sum_{f'=u,d,e} \sum_{i,j} \sqrt{m_{f'_i} m_{f'_j}} \bar{f}'_i \Big(\delta_{ij} + [\delta y_{f'}]_{ij} (\cos\phi^{f'}_{ij} - i \sin\phi^{f'}_{ij} \gamma^5)\Big) f'_j,$$

  - We follow the Higgs basis defining conditions (LHCHXSWG-INT-2015-001)

- In universal theories,
  - Yukawa matrices are diagonal; ϕ=0; and the following universal relation hold:

$$\boxed{\delta y_u = \delta y_d = \delta y_e = \Delta\bar{\kappa}_F.}$$

RG evolution of the universal theories EFT

based on 1512.03056

Universal theories can flow to non-universal theories

- Though the full SMEFT parameter space must be closed under RG, the 16-dimensional subspace defining universal theories is not.
  - It is not meaningful to talk about running of oblique parameters without additional prescriptions.
  - Use of oblique parameters is not a priori justified at the EW scale (where the theory is non-universal).

- Two example observables: $R_\ell \equiv \Gamma_{\text{had}}/\Gamma(Z \to \ell^+\ell^-)$, $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma_{\text{had}}$

  - *Our RG analysis in 1512.03056 makes use of the recently calculated anomalous dimensions of dimension-6 operators:*
    - *Jenkins, Manohar, Trott, 1308.2627, 1310.4838.*
    - *Alonso, Jenkins, Manohar, Trott, 1312.2014.*

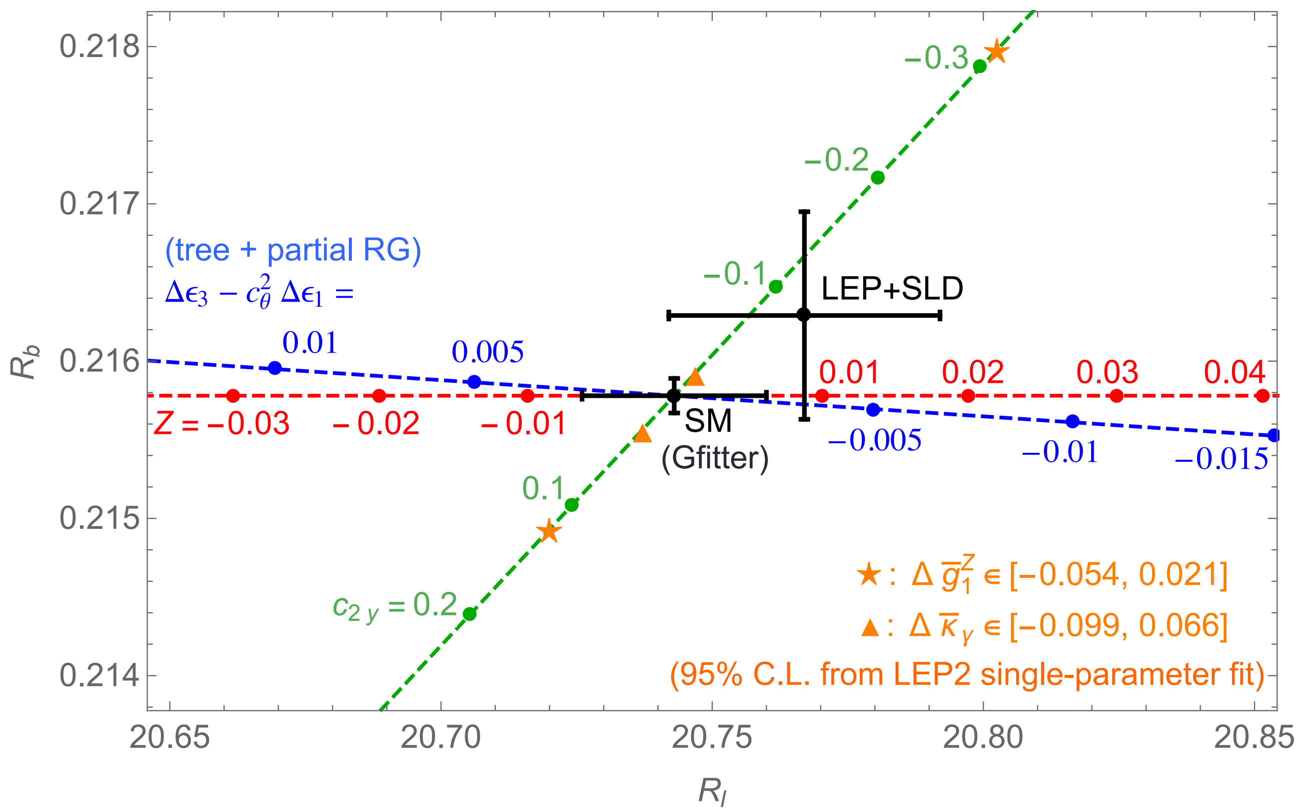
defined with prescriptions to absorb partial RG effects

$$\Delta\epsilon_1 \equiv \hat{T} - W - \frac{s_\theta^2}{c_\theta^2}Y, \quad \Delta\epsilon_3 \equiv \hat{S} - W - Y.$$

$$\bar{\delta}^{\rm NP} R_\ell = -0.36\big[\Delta\epsilon_3(\mu_{\rm EW}) - c_\theta^2 \Delta\epsilon_1(\mu_{\rm EW})\big] + \frac{\ln(\Lambda/\mu_{\rm EW})}{3}\big(0.13 Z - 0.053\Delta\bar{g}_1^Z + 0.0028\Delta\bar{\kappa}_\gamma - 0.0091 c_{2y}\big),$$

$$\bar{\delta}^{\rm NP} R_b = 0.079\big[\Delta\epsilon_3(\mu_{\rm EW}) - c_\theta^2 \Delta\epsilon_1(\mu_{\rm EW})\big] + \frac{\ln(\Lambda/\mu_{\rm EW})}{3}\big(-0.19\Delta\bar{g}_1^Z + 0.010\Delta\bar{\kappa}_\gamma - 0.032 c_{2y}\big),$$

other phenomenological parameters characterizing universal theories (linear combinations of Wilson coefficients)



- The oblique parameters fit must be extended for consistency beyond LO. (Note: still 16 underlying free parameters.)

Examples of RG-induced non-universal effects

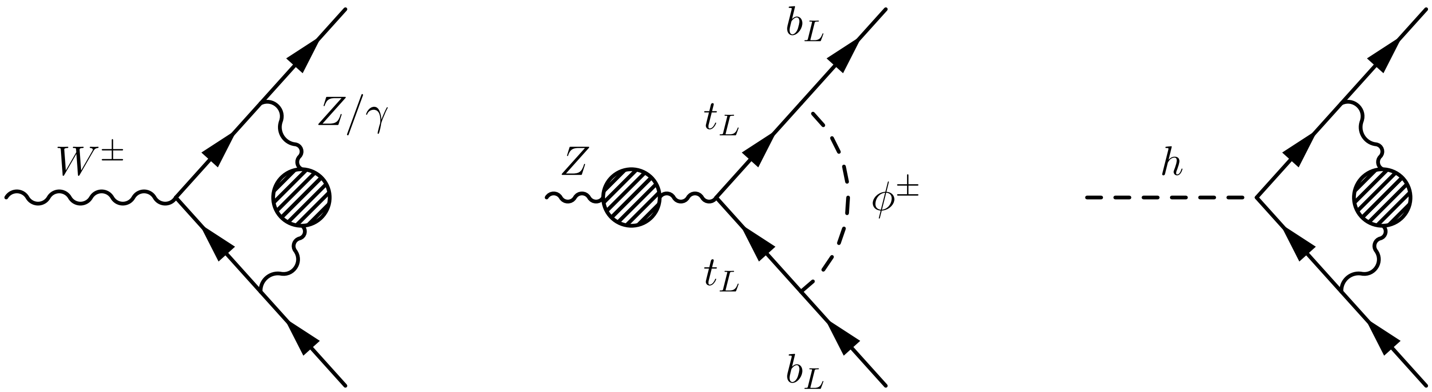


Figure 1. Examples showing how nonuniversal effects can be generated by universal oblique corrections. **Left:** effective Wqq' and $W\ell\nu$ couplings are renormalized differently, due to the different couplings of quarks and leptons to neutral gauge bosons. **Middle:** the $Zb_L\bar{b}_L$ coupling is singled out among all the $Zf\bar{f}$ couplings probed by Z-pole measurements for relatively large running effects proportional to y_t^2, via loop corrections involving the charged Goldstone boson (or the longitudinal $W^{\pm}$ if one uses the unitary gauge). **Right:** the Higgs boson couplings to the up- and down-type quarks and leptons are renormalized differently, due to different gauge interactions of the fermions. In each example, the interactions generated for the SM fermions are not in the form of the SM currents, and thus the corresponding operators cannot be eliminated in favor of bosonic operators. These examples, as well as many others, can be more rigorously formulated in terms of $SU(2)_L \times U(1)_Y$ invariant operators, but we prefer to give a more intuitive illustration at this stage. The arguments here will be made concrete in sections 3 and 4.

Challenge: how to define oblique parameters at the EW scale?

- Our strategy:
  - With additional prescriptions, separate RG evolution into universal and non-universal parts.
  - Absorb the universal part into the running of oblique parameters.
  - Account for non-universal part separately when calculating observables.

- With our prescriptions in 1512.03056,
  - The non-universal part is practically negligible for most EW observables.
  - Exceptions are those involving t_L, b_L, t_R (due to y_t~1).
    - Two examples:

$$R_\ell \equiv \Gamma_{\text{had}}/\Gamma(Z \to \ell^+\ell^-) \qquad R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma_{\text{had}}$$

Running of oblique parameters

$$\begin{aligned}
\hat{S}(\mu_{\rm EW}) &= \hat{S}(\Lambda) - \frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}\dot{\hat{S}}, \\
\hat{T}(\mu_{\rm EW}) &= \hat{T}(\Lambda) - \frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}\dot{\hat{T}}, \\
W(\mu_{\rm EW}) &= W(\Lambda) - \frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}\dot{W}, \\
Y(\mu_{\rm EW}) &= Y(\Lambda) - \frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}\dot{Y},
\end{aligned}$$

$$\begin{aligned}
\dot{\hat{S}} &= -\frac{1}{3}(19g^2 - g'^2)\hat{S} - \frac{1}{2}g^2\hat{T} - \frac{1}{3}(27g^2 - g'^2)c_\theta^2\Delta\bar{g}_1^Z + \frac{1}{6}(33g^2 + g'^2 + 24\lambda)\Delta\bar{\kappa}_\gamma + 2g^2\bar{\lambda}_\gamma \\
&\quad + \frac{1}{3}g^2\Delta\bar{\kappa}_V + \frac{1}{2}g^2(g^2 - g'^2)f_{z\gamma} + e^2g^2f_{\gamma\gamma} + 6y_t^2\hat{S} && (3.11a) \\
\dot{\hat{T}} &= \frac{3}{2}(3g^2 + 8\lambda)\left[\hat{T} - 2\frac{s_\theta^2}{c_\theta^2}(\hat{S} - \Delta\bar{\kappa}_\gamma)\right] - 24\lambda s_\theta^2\Delta\bar{g}_1^Z - 3g'^2\Delta\bar{\kappa}_V + 12y_t^2\hat{T} && (3.11b) \\
\dot{W} &= \frac{2}{3}g^2c_\theta^2\Delta\bar{g}_1^Z, && (3.11c) \\
\dot{Y} &= -\frac{2}{3}g'^2(\hat{S} + c_\theta^2\Delta\bar{g}_1^Z - \Delta\bar{\kappa}_\gamma). && (3.11d)
\end{aligned}$$

RG effects in the Yukawa sector

$$\delta y_t(\mu_{\rm EW}) - \delta y_b(\mu_{\rm EW}) = -\frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}(\delta\dot{y}_t - \delta\dot{y}_b)$$
$$= \frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}\Big[-6y_t^2(2\Delta\bar\kappa_F - \Delta\bar\kappa_V) + 4g'^2 s_\theta^2\Delta\bar g_1^Z - 2g'^2\frac{s_\theta^2}{c_\theta^2}\Delta\bar\kappa_\gamma$$
$$-2(g^2-2g'^2)\frac{s_\theta^2}{c_\theta^2}\hat S + y_t^2\hat T + (3y_t^2+2g'^2)W - \Big(\frac{41}{9}y_t^2 - \frac{16}{3}\lambda - 2g^2 + 4g'^2\Big)\frac{s_\theta^2}{c_\theta^2}Y$$
$$-\frac{128}{3}y_t^2\frac{g_s^2}{g^2}Z + 2(y_t^2-\lambda)y_t^2 c_{2y} + g'^2(e^2 f_{\gamma\gamma} - g'^2 f_{z\gamma})\Big]$$
$$\simeq \frac{\ln(\Lambda/\mu_{\rm EW})}{3}(-0.23\Delta\bar\kappa_F + 0.11\Delta\bar\kappa_V + 0.0022\Delta\bar g_1^Z - 0.0014\Delta\bar\kappa_\gamma - 0.0019\hat S + 0.019\hat T$$
$$+0.061W - 0.020Y - 2.8Z + 0.032c_{2y} + 0.00023f_{\gamma\gamma} - 0.00031f_{z\gamma}), \qquad (4.6a)$$

$$\delta y_b(\mu_{\rm EW}) - \delta y_\tau(\mu_{\rm EW}) = -\frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}(\delta\dot{y}_b - \delta\dot{y}_\tau)$$
$$= \frac{1}{16\pi^2}\ln\frac{\Lambda}{\mu_{\rm EW}}\Big[3y_t^2(\Delta\bar\kappa_F - \Delta\bar\kappa_V) - \frac{40}{3}g'^2 s_\theta^2\Delta\bar g_1^Z + \frac{20}{3}g'^2\frac{s_\theta^2}{c_\theta^2}\Delta\bar\kappa_\gamma$$
$$+4\Big(g^2 - \frac{10}{3}g'^2\Big)\frac{s_\theta^2}{c_\theta^2}\hat S - \Big(3y_t^2 + 4g'^2\Big)W - 4\Big(\frac{40}{9}\lambda + g^2 - \frac{10}{3}g'^2\Big)\frac{s_\theta^2}{c_\theta^2}Y$$
$$+\frac{128}{3}\lambda\frac{g_s^2}{g^2}Z - 2(y_t^2-\lambda)y_t^2 c_{2y} + 8g_s^4 f_{gg} - \frac{10}{3}g'^2(e^2 f_{\gamma\gamma} - g'^2 f_{z\gamma})\Big]$$
$$\simeq \frac{\ln(\Lambda/\mu_{\rm EW})}{3}(0.056\Delta\bar\kappa_F - 0.056\Delta\bar\kappa_V - 0.0074\Delta\bar g_1^Z + 0.0048\Delta\bar\kappa_\gamma - 0.000014\hat S$$
$$-0.066W - 0.013Y + 0.37Z - 0.032c_{2y} + 0.34f_{gg} - 0.00078f_{\gamma\gamma} + 0.0010f_{z\gamma}). \quad (4.6b)$$