EWSB meets flavor

(or how to learn about the Higgs without the Higgs)

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(based on collaborations with G. Buchalla, M. Jung and C. Krause)

Outline

- Motivation
- EFTs for EW interactions
- Heavy flavor semileptonic decays
- Summary

Motivation

- Higgs discovery at the LHC confirms the Standard Model as an excellent low-energy approximation to the electroweak interactions.

- One still needs to ascertain the nature of the Higgs particle and have a framework for new physics (hopefully appearing at the TeV scale). Both issues actually related.

- Assuming the existence of a mass gap, the most general model-independent way of parametrizing effects through EFT at the EW scale. Preferably, the framework should be general enough to test the Higgs hypothesis.

- Experimental side: LHC (Run II) will probe Higgs couplings through multi-Higgs production processes. However, prospects not as optimistic as initially believed.
  [Barr et al'14;Azatov et al'15]

- Does flavor physics have a saying in all this?

EFTs at the EW scale: the standard case

- The Higgs is in a weak doublet.
- The theory is renormalizable and new physics is decoupled.
- Expansion in canonical dimensions:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}_{d=6}$$

- Examples:

[Buchmueller et al'86;Grzadkowski et al'10]

$\psi^2\varphi^2 D$	
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

EFTs at the EW scale: the generic case

- Higgs not necessarily a doublet: h as singlet, EW Goldstones inside U.
- The theory is nonrenormalizable and new operators required to absorb divergences.
- Expansion in loops, or analogously in chiral dimensions [Buchalla, OC, Krause'14]

$$[\partial_\mu]_\chi = 1, \quad [\varphi]_\chi = [h]_\chi = 0, \quad [X_{\mu\nu}]_\chi = 1, \quad [\psi_{L,R}]_\chi = \frac{1}{2}, \quad [g]_\chi = [y]_\chi = 1$$

- Leading order Lagrangian: [Contino et al.'10; Buchalla, O.C., Krause'13]

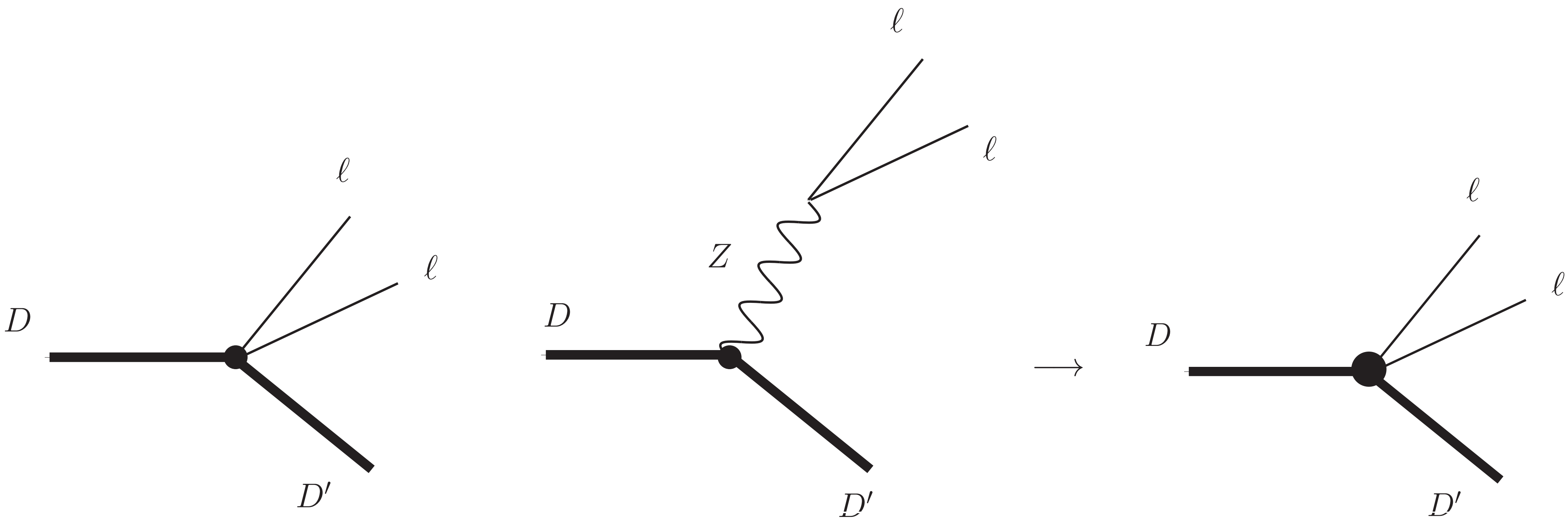
$$\mathcal{L}_{(\chi=2)} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{1}{2}\partial_\mu h \partial^\mu h$$
$$+ \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger\rangle f_U(h) - v\left[\bar{\psi} f_\psi(h) U P_\pm \psi + \text{h.c.}\right] - V(h)$$

with

$$f_U(h) = 1 + \sum_j a_j^U \left(\frac{h}{v}\right)^j; \quad f_\psi(h) = Y_\psi + \sum_j Y_\psi^{(j)} \left(\frac{h}{v}\right)^j; \quad V(h) = \sum_{j\geq 2} a_j^V \left(\frac{h}{v}\right)^j$$

EFTs for flavor physics

- Only incorporate the symmetries at the threshold $\Lambda = m_Q$: electromagnetic and strong.
- Matching to the EW EFT(s) will exploit the full SM symmetry. Tree-level matching easily done by integrating heavy (EW) degrees of freedom. [Alonso et al'14]



- How can this be relevant? No Higgs final states but imprint of EWSB!

Physics of semileptonic decays

- Consider the EFT for $D \to D'\ell\ell$ decays at $\Lambda = m_Q$:

$$\mathcal{L}_{\text{eff}}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\lambda_{ts}\frac{e^2}{(4\pi)^2}\sum_i^{12} C_i^{(d)}\mathcal{O}_i^{(d)}$$

where

$$\begin{aligned}
\mathcal{O}_7^{(\prime)} &= \frac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_{R(L)}b)F_{\mu\nu}; & & \\
\mathcal{O}_9^{(\prime)} &= (\bar{s}\gamma_\mu P_{L(R)}b)\ \bar{l}\gamma^\mu l; & \mathcal{O}_{10}^{(\prime)} &= (\bar{s}\gamma_\mu P_{L(R)}b)\ \bar{l}\gamma^\mu\gamma_5 l \\
\mathcal{O}_S^{(\prime)} &= (\bar{s}P_{R(L)}b)\ \bar{l}l; & \mathcal{O}_P^{(\prime)} &= (\bar{s}P_{R(L)}b)\ \bar{l}\gamma_5 l \\
\mathcal{O}_T &= (\bar{s}\sigma_{\mu\nu}b)\ \bar{l}\sigma^{\mu\nu}l; & \mathcal{O}_{T5} &= (\bar{s}\sigma_{\mu\nu}b)\ \bar{l}\sigma^{\mu\nu}\gamma_5 l
\end{aligned}$$

- Do the matching to the linear and nonlinear EFTs run down from the EW scale.

Dipole operators

- Relevant operators from the nonlinear EFT:

$$\mathcal{O}_{X1,2} = g'\bar{q}\sigma^{\mu\nu}UP_\pm rB_{\mu\nu};\ \mathcal{O}_{X3,4} = g\bar{q}\sigma^{\mu\nu}UP_\pm r\langle\hat{\tau}_3 W_{\mu\nu}\rangle$$
$$\mathcal{O}'_{X1,2} = g'\bar{r}P_\pm U^\dagger\sigma^{\mu\nu}qB_{\mu\nu};\ \mathcal{O}'_{X3,4} = g\bar{r}P_\pm U^\dagger\sigma^{\mu\nu}q\langle\hat{\tau}_3 W_{\mu\nu}\rangle$$

  In the unitary gauge, 1-to-1 correspondence with linear operators.

- Matching relation:

$$\delta C_7^{(\prime)} = \frac{8\pi^2}{m_b\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c_{X2}^{(\prime)} + c_{X4}^{(\prime)}\right]$$

- Very insensitive to Higgs (and thus Higgs nature). To be expected: dipole operators are not counterterms, *i.e.* they are effectively decoupled from the dynamics triggering EWSB.

Vectorial sector

- Relevant operators fall into two categories: those entering nonlocal diagrams

$$\mathcal{O}_{V1} = -\bar{q}\gamma^\mu q \langle \hat{\tau}_3 L_\mu \rangle; \qquad \mathcal{O}_{V2} = -\bar{q}\gamma^\mu \hat{\tau}_3 q \langle \hat{\tau}_3 L_\mu \rangle$$

$$\mathcal{O}_{V3} = -\bar{u}\gamma^\mu u \langle \hat{\tau}_3 L_\mu \rangle; \qquad \mathcal{O}_{V4} = -\bar{d}\gamma^\mu d \langle \hat{\tau}_3 L_\mu \rangle$$

and local ones:

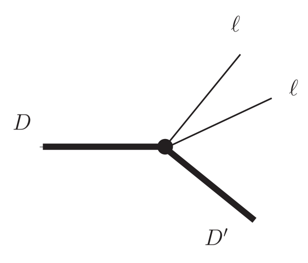
$$\mathcal{O}_{LL1} = \bar{q}\gamma^\mu q \; \bar{l}\gamma_\mu l; \qquad \mathcal{O}_{LL2} = \bar{q}\gamma^\mu \tau^j q \; \bar{l}\gamma_\mu \tau^j l$$

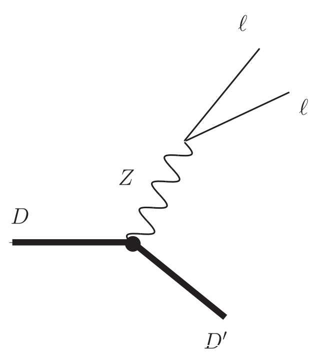
$$\hat{\mathcal{O}}_{LL3} = \bar{q}\gamma^\mu \hat{\tau}_3 q \; \bar{l}\gamma_\mu l; \qquad \hat{\mathcal{O}}_{LL4} = \bar{q}\gamma^\mu q \; \bar{l}\gamma_\mu \hat{\tau}_3 l$$

$$\hat{\mathcal{O}}_{LL5} = \bar{q}\gamma^\mu \hat{\tau}_3 q \; \bar{l}\gamma_\mu \hat{\tau}_3 l; \qquad \hat{\mathcal{O}}_{LL6} = \bar{q}\gamma^\mu \hat{\tau}_3 l \; \bar{l}\gamma_\mu \hat{\tau}_3 q$$

$$\hat{\mathcal{O}}_{LL7} = \bar{q}\gamma^\mu \hat{\tau}_3 l \; \bar{l}\gamma_\mu q$$

$$\mathcal{O}_{RR1} = \bar{u}\gamma^\mu u \bar{e}\gamma_\mu e; \qquad \mathcal{O}_{RR2} = \bar{d}\gamma^\mu d \; \bar{e}\gamma_\mu e$$





Vectorial sector

$$\delta C_9 = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[C_{LR} + C_{LL} - 4\frac{g_V}{v^2}C_{VL}\right];$$
$$\delta C_{10} = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[C_{LR} - C_{LL} + 4\frac{g_A}{v^2}C_{VL}\right];$$
$$C_9' = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[C_{RR} + C_{RL} - 4\frac{g_V}{v^2}C_{VR}\right];$$
$$C_{10}' = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[C_{RR} - C_{RL} + 4\frac{g_A}{v^2}C_{VR}\right]$$

with coefficients

$$C_{LL} = c_{LL1} + c_{LL2} - \hat{c}_{LL3} - \hat{c}_{LL4} + \hat{c}_{LL5} + \hat{c}_{LL6} - \hat{c}_{LL7}; \quad C_{RR} = c_{RR2}$$
$$C_{LR} = c_{LR1} - \hat{c}_{LR5}; \quad C_{RL} = c_{LR3} - \hat{c}_{LR7}; \quad C_{VL} = c_{V1} - c_{V2}; \quad C_{VR} = c_{V4}$$

- Notation: unhatted operators have linear counterparts in unitary gauge; unhatted ones are genuinely nonlinear.
- Rather insensitive to the Higgs nature. Genuine nonlinear operators (hatted) present but do not change the qualitative picture.

Scalar and tensor sector

- Three categories of operators:

$$\mathcal{O}_{LR4} = \bar{q}\gamma^{\mu} l \; \bar{e}\gamma_{\mu} d; \qquad \hat{\mathcal{O}}_{LR8} = \bar{q}\gamma^{\mu}\hat{\tau}_3 l \; \bar{e}\gamma_{\mu} d$$

$$\mathcal{O}_{S1} = \epsilon_{ij}\bar{q}^i u \bar{l}^j e; \qquad \mathcal{O}_{S2} = \epsilon_{ij}\bar{q}^i \sigma_{\mu\nu} u \bar{l}^j \sigma^{\mu\nu} e$$

$$\hat{\mathcal{O}}_{S3} = \bar{q}UP_+ r\bar{l}UP_-\eta; \qquad \hat{\mathcal{O}}_{S4} = \bar{q}\sigma_{\mu\nu}UP_+ r\bar{l}\sigma^{\mu\nu}UP_-\eta$$

$$\hat{\mathcal{O}}_{Y1} = \bar{q}UP_- r\bar{l}UP_-\eta; \qquad \hat{\mathcal{O}}_{Y2} = \bar{q}\sigma_{\mu\nu}UP_- r\bar{l}\sigma^{\mu\nu}UP_-\eta$$

$$\hat{\mathcal{O}}_{Y3} = \bar{l}UP_-\eta\bar{r}P_+U^{\dagger}q; \qquad \hat{\mathcal{O}}_{Y4} = \bar{l}UP_- r\bar{r}P_+U^{\dagger}l$$

- The first category can be Fierzed to a scalar-scalar structure.
- The second category does not contribute to $D \to D'\ell\ell$ (but it does to $U \to U'\ell\ell$).
- The third category has peculiar hypercharge structure, which is exclusive of the nonlinear case (at NLO).

Scalar and tensor sector

Matching relations:

$$C_S = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c_S + \hat{c}_{Y1}\right]; \qquad C_P = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[-c_S + \hat{c}_{Y1}\right]$$

$$C'_S = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c'_S + \hat{c}'_{Y1}\right]; \qquad C'_P = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c'_S - \hat{c}'_{Y1}\right]$$

$$C_T = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[\hat{c}_{Y2} + \hat{c}'_{Y2}\right]; \qquad C_{T5} = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[\hat{c}_{Y2} - \hat{c}'_{Y2}\right]$$

with

$$c_S^{(\prime)} = 2(\hat{c}_{LR8}^{(\prime)} - c_{LR4}^{(\prime)})$$

- Strong correlations in the linear case [Alonso et al'14]

  $$C_S = -C_P; \qquad C'_S = C'_P; \qquad C_T = C_{T5} = 0$$

  valid up to NNLO corrections.

- The nonlinear case erases the correlations in the scalar sector and brings NLO contributions to the tensor operators. Rather clean signatures of linear *vs* nonlinear, experimentally testable at B factories.

Nontrivial hypercharge structures from BSM

Nonvanishing fermionic hypercharge operators generated at NNLO in the linear case. In the nonlinear case, they can be generated in simple models of heavy scalar exchanges. Consider the interactions of a singlet φ and a $(\bar{\mathbf{3}},\mathbf{2})_{-\mathbf{2/3}}$ leptoquark Φ to fermionic scalar currents:

$$\begin{aligned}\mathcal{L}_{int}(\varphi,\Phi) = {}& \lambda_u \bar{q} U P_+ \varphi r + \lambda_d \bar{q} U P_- \varphi r + \lambda_e \bar{l} U P_- \varphi \eta \\ & + \lambda_1 \bar{l} U P_+ \Phi r + \lambda_2 \bar{l} U P_- \Phi r + \lambda_3 \bar{\eta} P_- U^\dagger \Phi q + \mathrm{h.c.}\end{aligned}$$

Integrating out the heavy scalars one gets:

$$\begin{aligned}\mathcal{L}_{eff} = {}& \frac{\lambda_u^* \lambda_e}{2m_\varphi^2}\mathcal{O}_{FY3} + \frac{\lambda_u \lambda_e}{2m_\varphi^2}\mathcal{O}_{ST3} + \frac{\lambda_d \lambda_e}{2m_\varphi^2}\mathcal{O}_{FY1} \\ & - \frac{\lambda_d \lambda_e^*}{8m_\varphi^2}\left(\mathcal{O}_{LR4} - \mathcal{O}_{LR8}\right) - \frac{\lambda_1^2}{8m_\Phi^2}\left(\mathcal{O}_{LR2} + \mathcal{O}_{LR6}\right) \\ & - \frac{\lambda_2^2}{8m_\Phi^2}\left(\mathcal{O}_{LR3} - \mathcal{O}_{LR7}\right) - \frac{\lambda_3^2}{8m_\Phi^2}\left(\mathcal{O}_{LR1} - \mathcal{O}_{LR5}\right) \\ & + \frac{\lambda_1 \lambda_2}{2m_\Phi^2}\mathcal{O}_{FY4} - \frac{\lambda_1 \lambda_3}{4m_\Phi^2}\left(\mathcal{O}_{ST3} - \frac{1}{4}\mathcal{O}_{ST4}\right) \\ & - \frac{\lambda_2 \lambda_3}{4m_\Phi^2}\left(\mathcal{O}_{FY1} - \frac{1}{4}\mathcal{O}_{FY2}\right) + \mathrm{h.c.}\end{aligned}$$

Conclusions

- Incorporating the full SM symmetry into the EFT for flavor processes is informative, not only for flavor processes, but also for Higgs physics.

- Heavy flavor semileptonic decays cannot be used to measure Higgs couplings but can be the easiest way to learn about the dynamics of EWSB.

- Strong correlations in the scalar/tensor sectors are not due to EW symmetry alone, but a consequence of assuming a SM Higgs. They get erased as soon as one relaxes the hypothesis and therefore are a good testing ground for weak or strongly-coupled new physics behind EWSB.

- The EFT basis used so far for flavor processes remains a basis in the nonlinear (more generic) EW EFT framework.