Higgs EFTs and signatures of a nonstandard Higgs from flavor physics

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

Outline

- Motivation
- EFTs for EW interactions
- EFT at the LHC
- EWSB meets flavor (*or how to learn about the Higgs without the Higgs*)
- Summary and outlook

Motivation

- Higgs discovery at the LHC confirms the Standard Model as an excellent low-energy approximation to the electroweak interactions. Higgs couplings currently SM-like to $\mathcal{O}(10\%)$.

- 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]

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

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$	
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

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

EFT for generic EWSB

MAIN ASSUMPTIONS:

- **Strongly-coupled dynamics** at the scale $f < \Lambda_W$ triggering EWSB [Longhitano'80,81; Appelquist et al'80,93]. Natural strong cutoff of the theory: (dynamically generated) $\Lambda_S \sim 4\pi f \sim (5-10)$ TeV. Weak cutoffs Λ_W can exist but higher up.

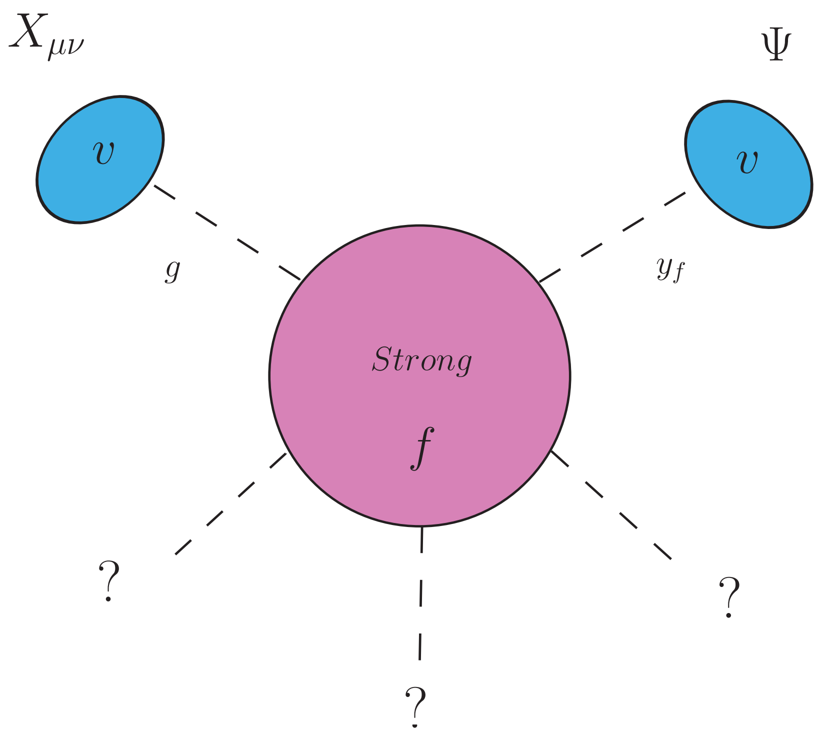
- **Minimal EWSB pattern**: $SU(2)_L \times SU(2)_R \to SU(2)_V$ with $SU(2)_L \times U(1)_Y$ gauged. Most general with the minimal particle content (3 Goldstone bosons to account for the longitudinal modes of the W and Z). Collected in a nonlinear realization inside $U(x) \to g_L U(x) g_R^\dagger$.

- **Soft custodial symmetry breaking**: T-parameter contribution at NLO.

- Gauge bosons weakly coupled to the strong sector.

- **Light scalar** h as a SM singlet (pGB of a more general symmetry group) [Ferruglio'93; Contino et al.'10]. It can always be tuned to the SM Higgs but comprises more general scenarios.

Scales of the problem



- Multiscale problem: v, f, $\Lambda = 4\pi f$. Dynamics is described with the dimensionless parameters

$$\xi = \frac{v^2}{f^2} \qquad\qquad \ell = \frac{f^2}{\Lambda^2} \sim \frac{1}{16\pi^2}$$

- Strong sector can be decoupled, *e.g.* vacuum misalignment mechanism [Georgi et al'84]. SM recovered as a limiting case.

EFT for generic EWSB

MULTISCALE EXPANSION:

$$\ell = \frac{f^2}{\Lambda^2}; \qquad \xi = \frac{v^2}{f^2}; \qquad d = \frac{v^2}{\Lambda_W^2}$$

- Strongly-coupled regime: $f \sim v << \Lambda_W$. Loop expansion with $\mathcal{L}_{LO} \neq \mathcal{L}_{SM}$.
- Strong-dominated dynamics: $v < f << \Lambda_W$. Hybrid expansion in (ℓ, ξ).
- Weak-dominated dynamics: $\Lambda_W < f$. Effectively a dimensional expansion.
- Pure Standard Model: $f, \Lambda_W \to \infty$.

At present, experimental bound at $\xi \sim 10^{-1}$ vs $\ell \sim 10^{-2}$. Strong-dominated dynamics is the setting to explore given the current precision.

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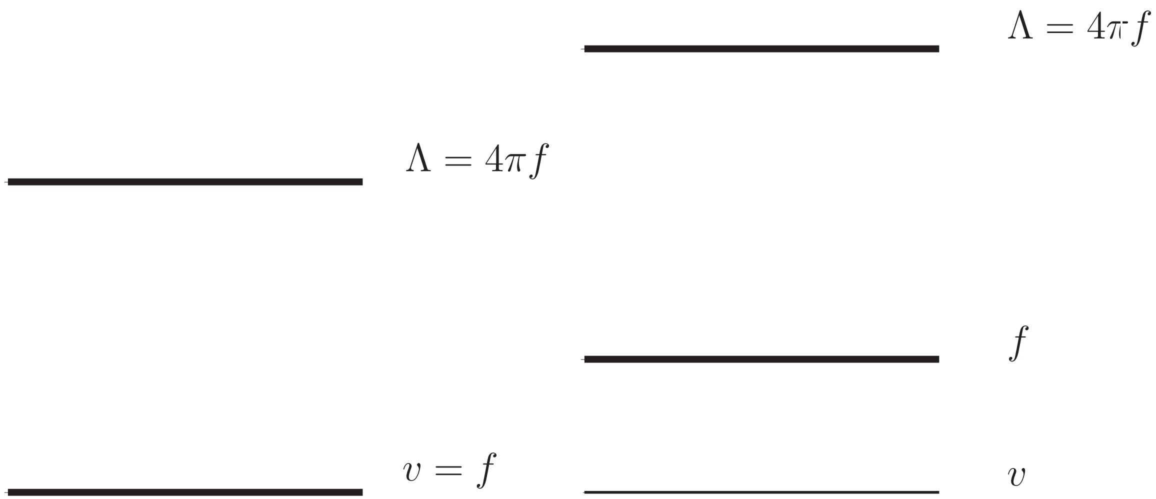
Playing with the ξ knob

- Transition between nondecoupling (composite) and decoupling (fundamental) interactions.



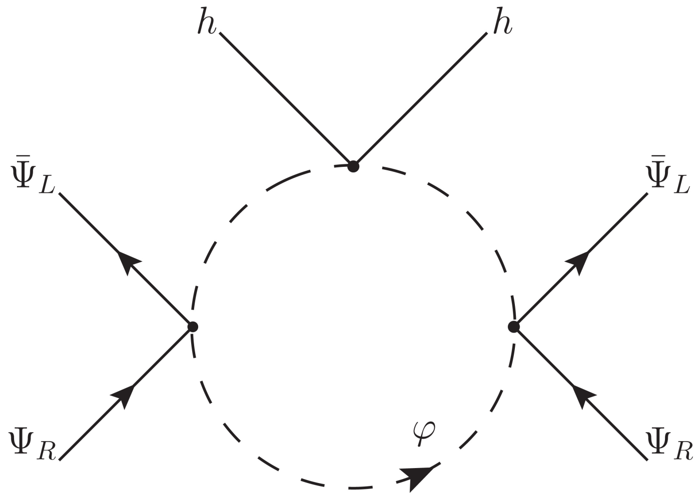
- The transition can be gauged with the decoupling parameter $\xi = \dfrac{v^2}{f^2}$:

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

  - $\xi \to 1$: ~~Strongly coupled regime~~
  - $\ell < \xi < 1$: Strong-dominated dynamics (hybrid expansion in (ℓ, ξ)).

Some reflections on power-counting

- Decoupling EFTs: dimensional counting ($1/\Lambda^2$ expansion).
- Non-decoupling EFTs: loop counting ($f^2/\Lambda^2 \sim 1/(16\pi^2)$ expansion). ξ is only a decoupling parameter.
- In some simplified cases strongly-coupled EFTs can be cast as a dimensional expansion, *e.g.* pure ChPT (expansion in derivatives).
- When weakly and strongly-coupled sectors mix (as is the case here), the picture gets complicated. Basic requirements of a power-counting: Homogeneity of the LO Lagrangian. NLO renormalizes the nondecoupling divergences.



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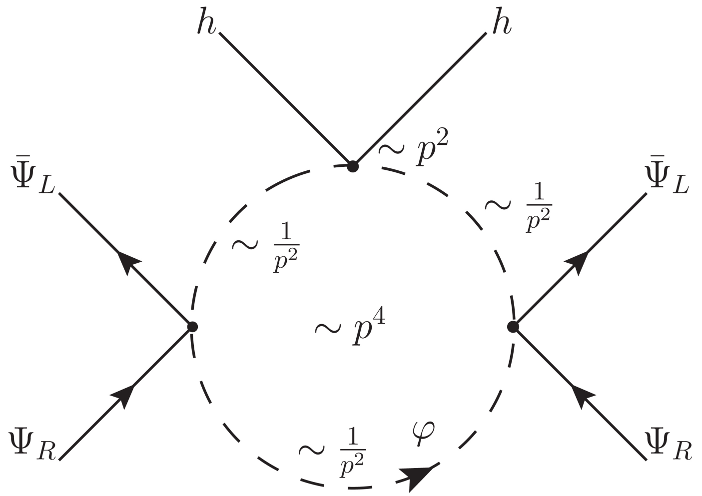
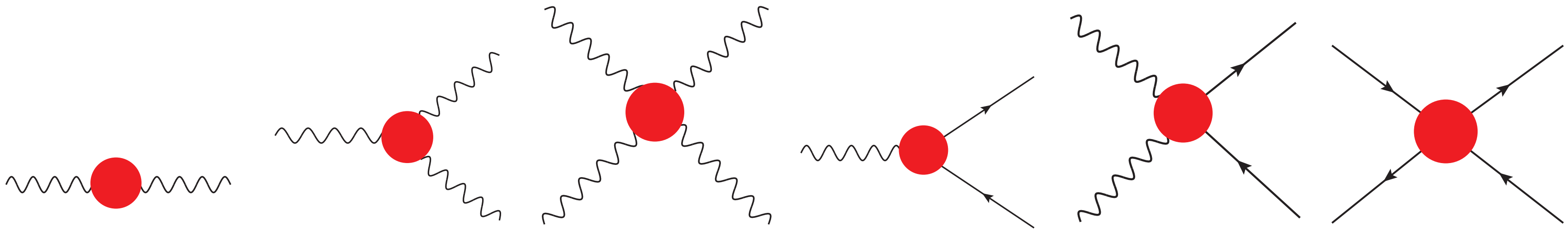


Nonlinear EFT at NLO

Operator building at every order: assemble building blocks (U, ψ, X and derivatives) in accordance with the power-counting formula.

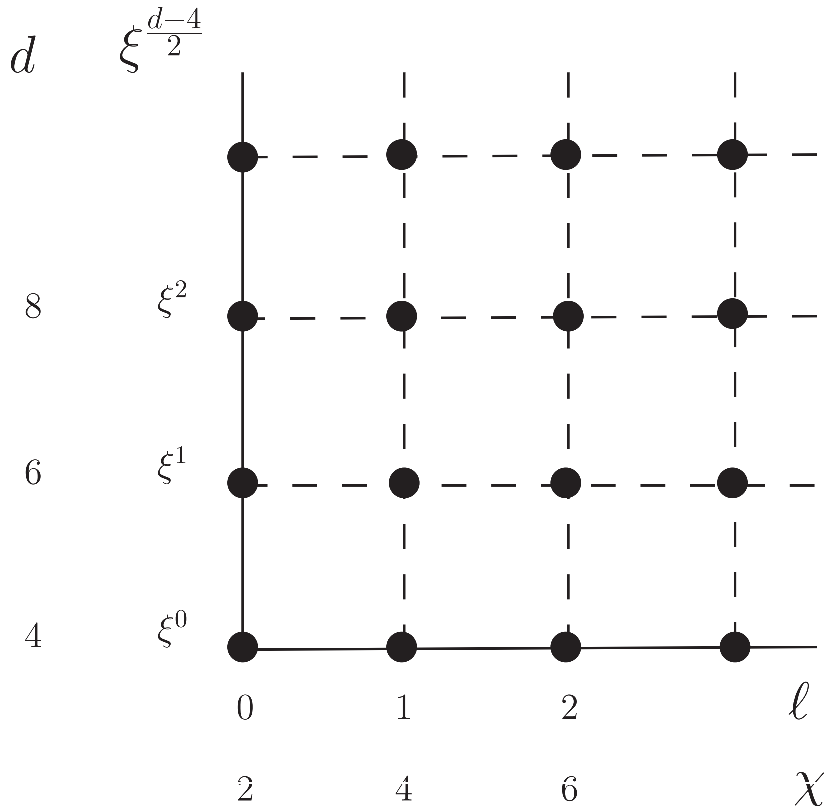
- NLO: 6 classes, which correspond to corrections to the vertices



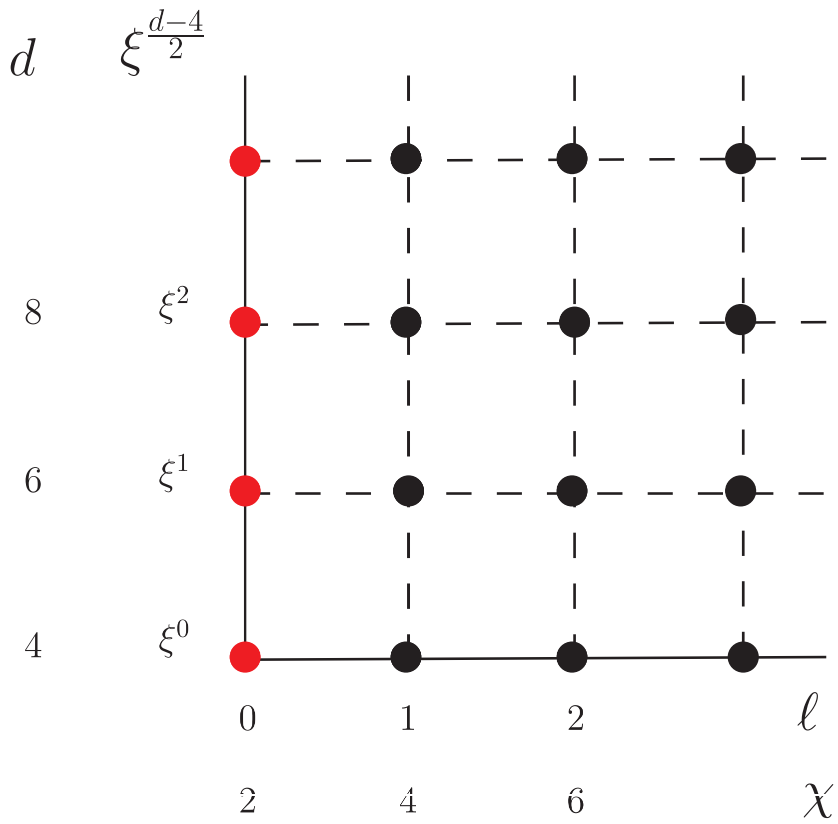
with an arbitrary number of Higgs insertions.

- Of relevance in processes that are subleading (loop-suppressed) in the SM, *e.g.*, $h \to \gamma\gamma$, $h \to gg$, $h \to Z\gamma$.

Loop vs dimensional expansion

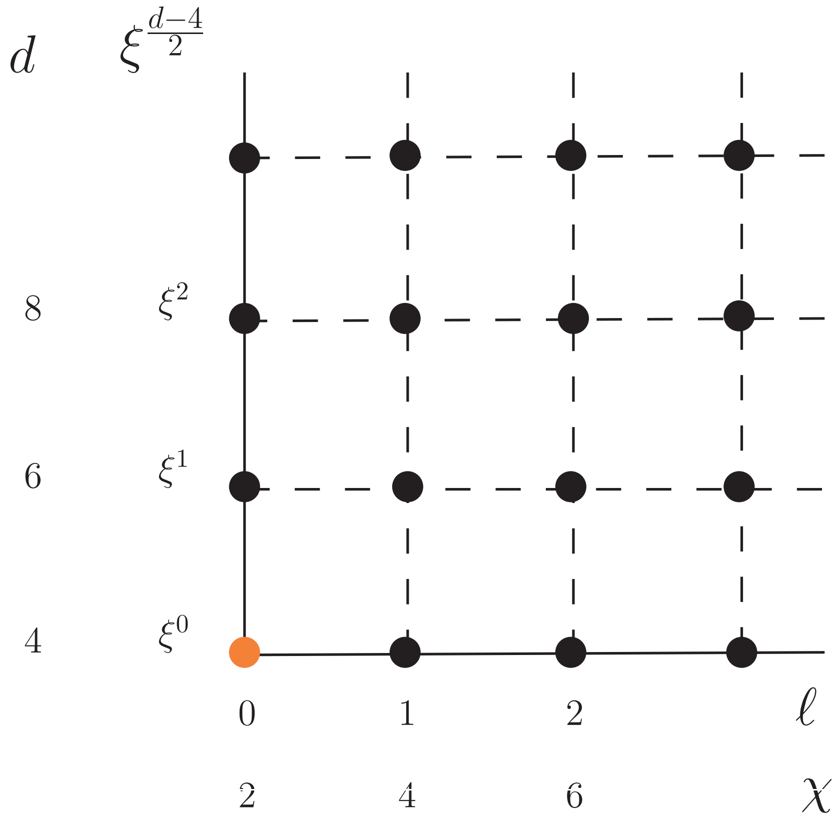


Loop vs dimensional expansion



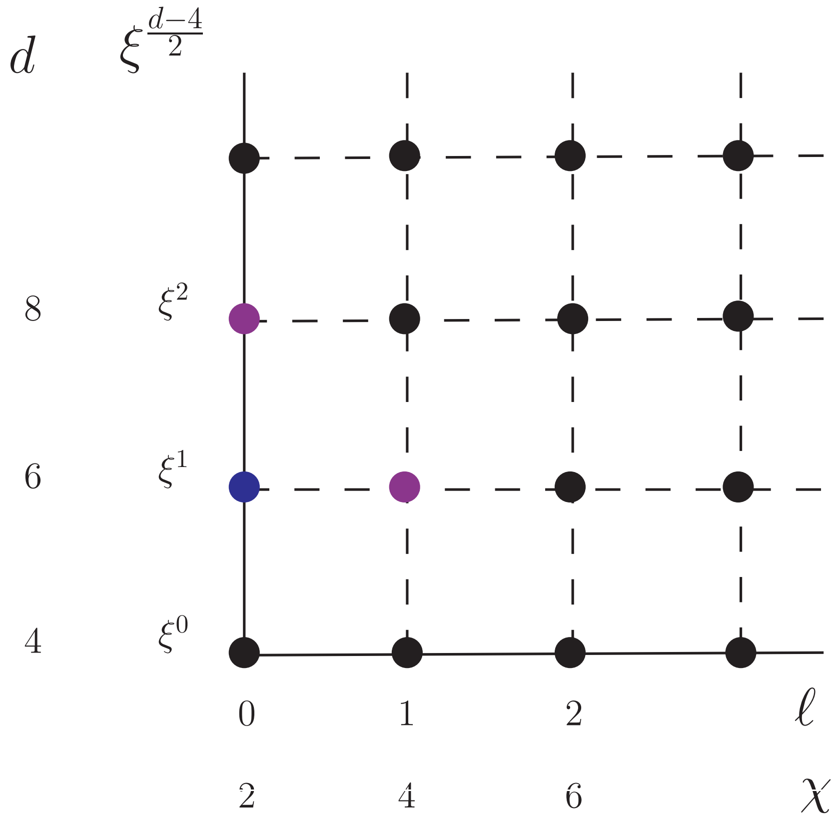
- $\mathcal{L}_{LO}$ amounts to a resummation of the ξ expansion.

Loop vs dimensional expansion



- $\mathcal{L}_{SM}$ is recovered from $\mathcal{L}_{LO}$ when $\xi \to 0$.

Loop vs dimensional expansion



- Beyond LO in the double expansion: $\mathcal{L}_{LO}(\xi^2)$ is in general more important than $\mathcal{L}_{NLO}(\xi)$.

$$\xi = \frac{v^2}{f^2}; \qquad \frac{\xi}{16\pi^2} = \frac{v^2}{f^2}\left(\frac{f^2}{\Lambda^2}\right); \qquad \xi^2 = \frac{v^2}{f^2}\left(\frac{v^2}{f^2}\right)$$

Example: $SO(5)/SO(4)$ model

- $G = SO(5) \times U(1)_X$ broken to $H_1 = SO(4) \times U(1)_X$
- Isomorphism: $H_1 \sim SU(2)_L \times SU(2)_R \times U(1)_X \supset G_{SM}$
- 4 real pGB h^A transforming under the fundamental of $SO(4)$:

$$\Sigma(h^A) = \exp(\sqrt{2} i t^A h^A / f)\Sigma_0, \qquad \Sigma_0 = \begin{pmatrix} 0_4 \\ 1 \end{pmatrix}$$

- Equivalently, bidoublet of $SU(2)$ (H, H^c). Defining

$$H = h_A \lambda_A \equiv hU, \qquad \vec{\lambda} = (i\vec{\sigma}, 1_2) \Longrightarrow \quad h_A = \frac{h}{2}\langle U \lambda_A^\dagger \rangle$$

one can express $\Sigma(h, U)$:

$$\Sigma(h, U) = \begin{pmatrix} \frac{\langle U \lambda_A^\dagger \rangle}{2} \sin h/f \\ \cos h/f \end{pmatrix}$$

Example: $SO(5)/SO(4)$ *model*

- (Bosonic) leading order term:

$$\frac{f^2}{2}\langle D_\mu \Sigma^\dagger D^\mu \Sigma\rangle = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{f^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle \sin^2\frac{h}{f}$$

$$= \frac{1}{2}\partial_\mu \hat{h}\partial^\mu \hat{h} + \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle f_U(\hat{h})$$

- Upon breaking, $h = \langle h\rangle + \hat{h}$:

(i) v **dynamically generated**. Matching to the gauge boson masses:

$$v = f\sin\frac{\langle h\rangle}{f} \quad\Longrightarrow\quad \xi = \sin^2\frac{\langle h\rangle}{f}$$

(ii) In this particular model

$$f_U(\hat{h},\xi) = \cos\frac{2\hat{h}}{f} + \frac{\sqrt{1-\xi^2}}{\xi}\sin\frac{2\hat{h}}{f} + \frac{1}{\xi^2}\sin^2\frac{\hat{h}}{f}$$

(iii) Linear and quadratic interactions:

$$f_U(\hat{h},\xi) = 1 + 2\sqrt{1-\xi}\left(\frac{\hat{h}}{v}\right) + (1-2\xi)\left(\frac{\hat{h}}{v}\right)^2$$

Small ξ limit

- In explicit models, ξ can be tracked down explicitly. In the EFT, the (resummed) ξ expansion hidden inside coefficients.

$$\mathcal{L}_{(\chi=2)} = -\frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + i\sum_j \bar{f}_j \not{D} f_j + \frac{1}{2}\partial_\mu h \partial^\mu h$$
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with

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

- Knowing that the ξ expansion acts like a dimensional expansion, the operator basis for $\mathcal{O}(\xi)$ terms has to be the same as the ordinary $d=6$ operator basis. The power-counting is however still a loop expansion.

- In practice, catalog the list of $d=6$ operators and rewrite them in the nonlinear basis using

$$\phi = \frac{v+h}{\sqrt{2}} U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

- Higher orders in the ξ expansion can be systematically incorporated.

EFT fitting strategy at the LHC

Run-2 prospects: [Numbers borrowed from H. Kroha at Aspen 2014]

$\Delta\mu/\mu[\%](300\ \text{fb}^{-1})$	$\gamma\gamma$	WW	ZZ	$\tau\tau$	bb	$\mu\mu$	$Z\gamma$
ATLAS	14 (9)	13 (8)	12 (6)	22 (16)	—	39 (38)	147 (145)
CMS	12 (6)	11 (6)	11 (7)	14 (8)	14 (11)	42 (40)	62 (62)

$\Delta\kappa/\kappa[\%](300\ \text{fb}^{-1})$	$\gamma\gamma$	WW	ZZ	gg	$\tau\tau$	bb	tt	$\mu\mu$	$Z\gamma$
ATLAS	13 (8)	8 (7)	8 (7)	11 (9)	18 (13)	κ_τ	22 (20)	23 (21)	79 (78)
CMS	7 (5)	6 (4)	6 (4)	8 (6)	8 (6)	13 (10)	15 (14)	23 (23)	41 (41)

Precision goal between $5-10\%$.

EFT fitting strategies at the LHC

STRATEGY 1: Assume

- The Standard Model is the leading-order description at low energies.
- The theory is renormalizable and so new physics is decoupled.
- The Higgs is a fundamental scalar in a $SU(2)$ doublet.

Then deviations come from the $1/\Lambda^2$ suppressed $d = 6$ operators.

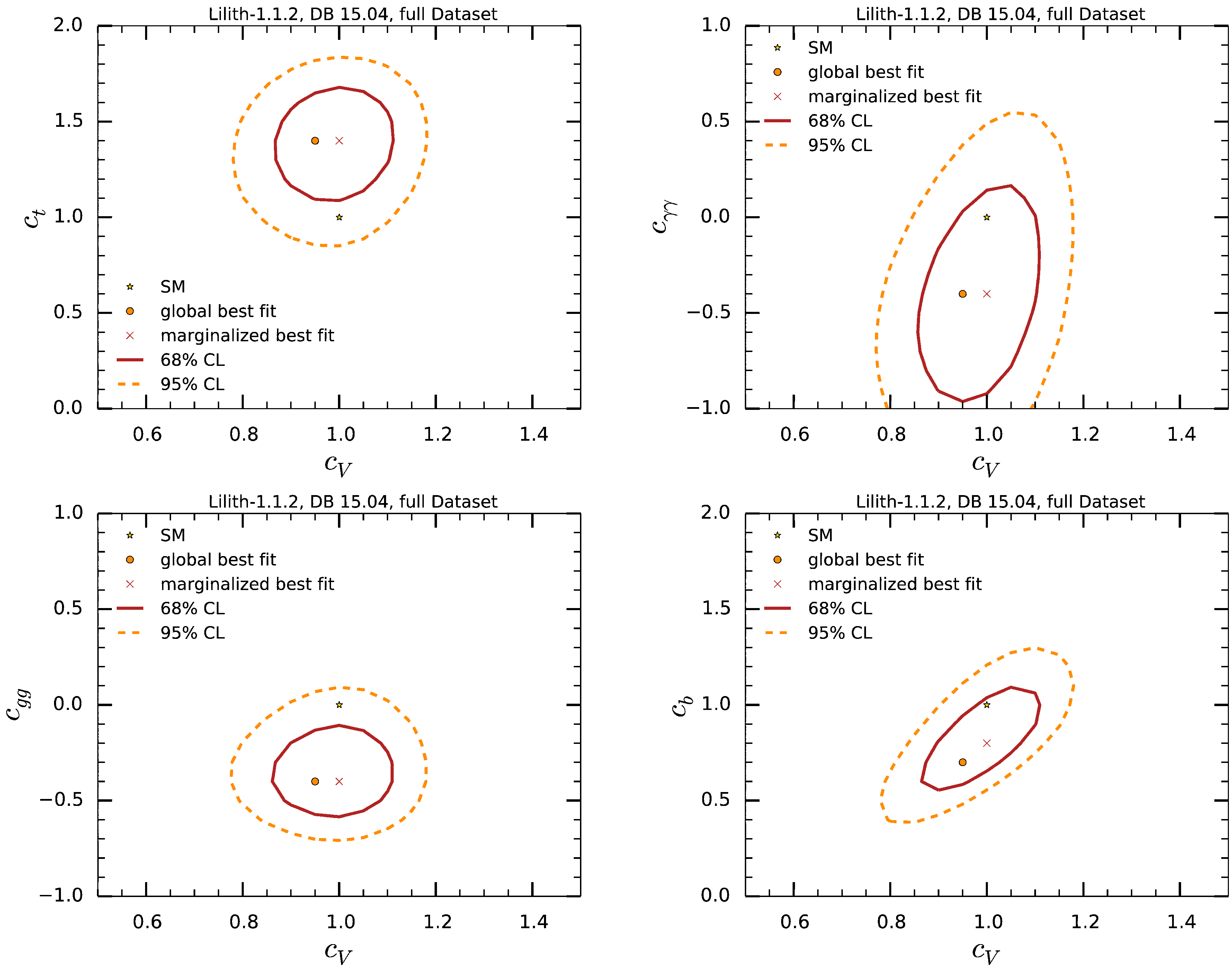
STRATEGY 2: Assume [Buchalla,O.C.,Celis,Krause'15]

- Basically nothing about the Higgs.

Experiment is allowing right now deviations in the SM couplings around $10 - 20\%$. The biggest effects are still described by the nonlinear EFT at LO. Fit to experimental data with only 6 parameters:

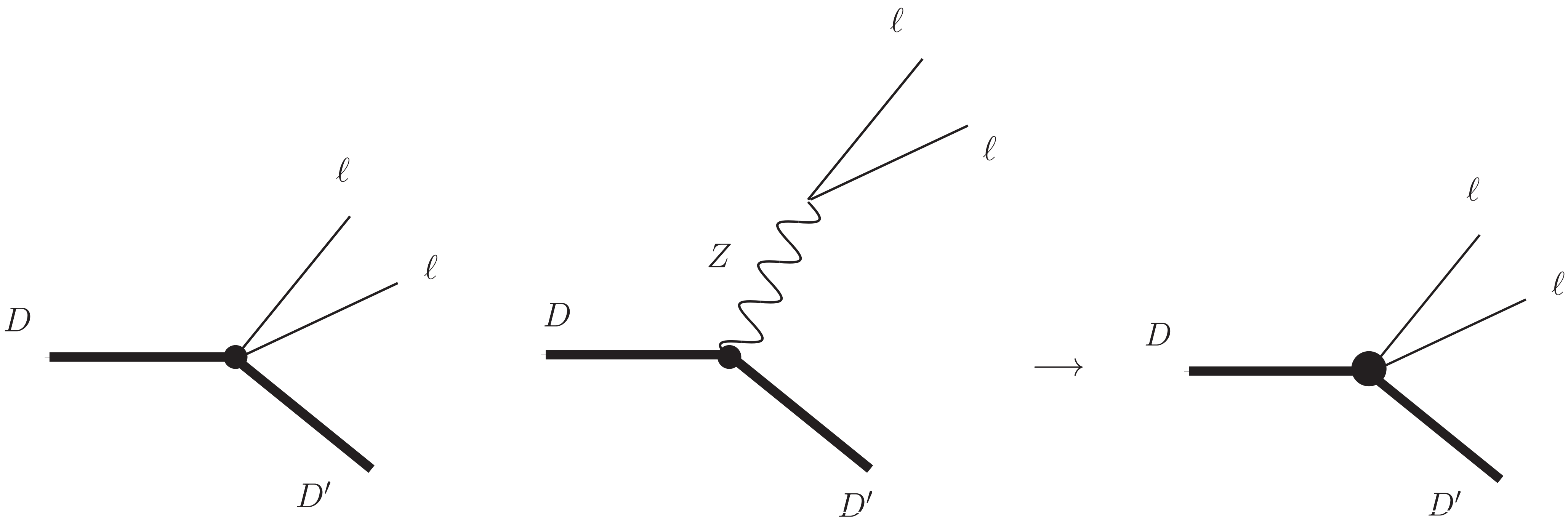
$$\mathcal{L} = 2c_V \left(m_W^2 W_\mu W^\mu + \frac{1}{2} Z_\mu Z^\mu \right) \frac{h}{v} - \sum_{f=t,b,\tau} c_f y_f \bar{f} f h + c_{gg} \frac{g_s^2}{16\pi^2} G_{\mu\nu} G^{\mu\nu} \frac{h}{v} + c_{\gamma\gamma} \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} \frac{h}{v}$$

Jumping to Strategy 1 is premature...


Lilith-1.1.2, DB 15.04, full Dataset
SM
global best fit
marginalized best fit
68% CL
95% CL
c_t
c_V
$c_{\gamma\gamma}$
c_{gg}
c_b

EWSB meets flavor

- Usual EFTs for flavor physics only incorporate symmetries present at threshold $\Lambda = m_Q$: $SU(3)_C$ and $U(1)_{EM}$.
- 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]



- Main message: this *is* relevant for Higgs physics. No Higgs final states but imprint of EWSB! [O.C., Jung'15]

Physics of semileptonic decays

- Consider the EFT for $D \to D'\ell\ell$ decays at hadronic scales $\Lambda \ll M_W$:

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

where

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_{R(L)}b)F_{\mu\nu};$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)\ \bar{l}\gamma^\mu l; \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)\ \bar{l}\gamma^\mu\gamma_5 l$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s}P_{R(L)}b)\ \bar{l}l; \qquad \mathcal{O}_P^{(\prime)} = (\bar{s}P_{R(L)}b)\ \bar{l}\gamma_5 l$$

$$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu}b)\ \bar{l}\sigma^{\mu\nu}l; \qquad \mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu}b)\ \bar{l}\sigma^{\mu\nu}\gamma_5 l$$

- Do the matching to the linear and nonlinear EFTs run down from the EW scale (integrate out EW fields).

Dipole operators

- Relevant operators from the nonlinear EFT:

$$\mathcal{O}_{X1,2} = g'\bar{q}\sigma^{\mu\nu}UP_{\pm}rB_{\mu\nu}; \qquad \mathcal{O}_{X3,4} = g\bar{q}\sigma^{\mu\nu}UP_{\pm}r\langle\hat{\tau}_3W_{\mu\nu}\rangle$$

$$\mathcal{O}'_{X1,2} = g'\bar{r}P_{\pm}U^{\dagger}\sigma^{\mu\nu}qB_{\mu\nu}; \qquad \mathcal{O}'_{X3,4} = g\bar{r}P_{\pm}U^{\dagger}\sigma^{\mu\nu}q\langle\hat{\tau}_3W_{\mu\nu}\rangle$$

  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

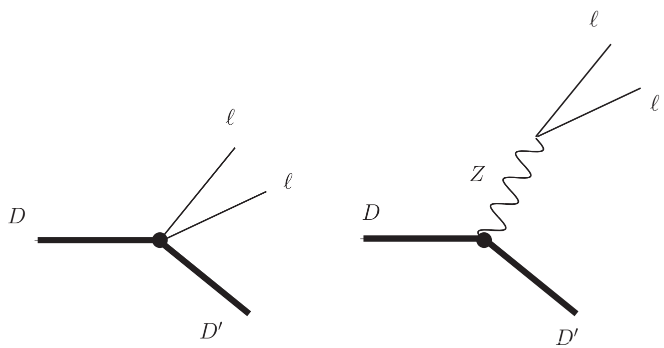
- Relevant operators fall into two categories: those entering nonlocal diagrams

$$\mathcal{O}_{V1} = -\bar{q}\gamma^\mu q\langle\hat{\tau}_3 L_\mu\rangle; \qquad \mathcal{O}_{V2} = -\bar{q}\gamma^\mu\hat{\tau}_3 q\langle\hat{\tau}_3 L_\mu\rangle$$
$$\mathcal{O}_{V3} = -\bar{u}\gamma^\mu u\langle\hat{\tau}_3 L_\mu\rangle; \qquad \mathcal{O}_{V4} = -\bar{d}\gamma^\mu d\langle\hat{\tau}_3 L_\mu\rangle$$

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

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

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

$$C'_9 = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[C_{RR} + C_{RL} + 4g_V\frac{\Lambda^2}{v^2}C_{VR}\right];$$

$$C'_{10} = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[C_{RR} - C_{RL} - 4g_A\frac{\Lambda^2}{v^2}C_{VR}\right]$$

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:

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

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

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

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

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

- 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]

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

  Not a consequence of $SU(2) \times U(1)_Y$ symmetry, but rather from Higgs nature.

- 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.

Conclusions

- EFTs are the right tool to extract unbiased information from experimental data. Important to pick the most generic one allowed by current status of experiments.

- At present, strong dynamics still allowed. The most conservative fitting procedure is to consider $\mathcal{L}_{LO} \neq \mathcal{L}_{SM}$. Very few parameters, ideal for the LHC (discovery machine). Justification and systematic extension of the so-called κ-formalism.

- Flavor physics may have a saying in determining the nature of the Higgs boson, especially if multi-Higgs processes turn out to be not so decisive at the LHC, as recently hinted at. One can still learn about the Higgs without the Higgs, especially in down-quark neutral semileptonic processes.