Higgs beyond the Standard Model
an Effective Field Theory approach
– Young Scientist Workshop Ringberg –

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Based on: "Complete Electroweak Chiral Lagrangian with a Light Higgs at NLO"
by G. Buchalla, O. Catà & C. Krause, [hep-ph/1307.5017; Nucl. Phys. B]

"On the Power Counting in Effective Field Theories"
by G. Buchalla, O. Catà & C. Krause, [hep-ph/1312.5624; Phys. Lett. B]

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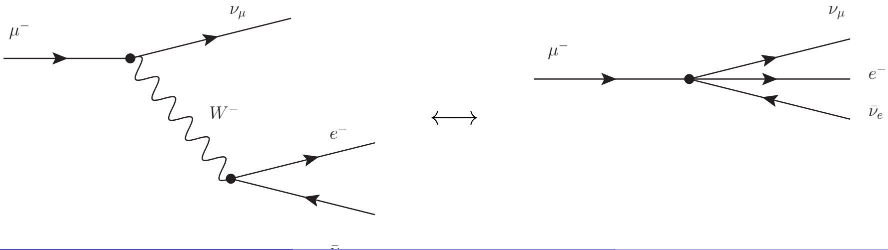
- Example: Fermi-Theory for weak interactions



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$\rightarrow$ Since any UV theory can be mapped on this basis the **bottom-up** approach provides a model independent analysis of new physics

The Standard Model as Effective Field Theory

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Standard Model Lagrangian

$$\begin{aligned}\mathcal{L}_{\mathsf{SM}} = &-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} \\ &+ \bar{q}i\not{D}q + \bar{\ell}i\not{D}\ell + \bar{u}i\not{D}u + \bar{d}i\not{D}d + \bar{e}i\not{D}e \\ &+ D_\mu\phi^\dagger D^\mu\phi + \mu^2\phi^\dagger\phi - \frac{\lambda}{2}(\phi^\dagger\phi)^2 \\ &- (\bar{q}Y_u\tilde{\phi}u + \bar{q}Y_d\phi d + \bar{\ell}Y_\ell\phi e + \text{h.c.})\end{aligned}$$

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Assume that the SM is a low-energy effective theory of some new physics.

How do the terms at higher orders look like?

Building up the higher order terms

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- scalar h and Goldstones form Higgs-doublet ϕ
- theory becomes renormalizable
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- include h as scalar singlet
- theory stays non-renormalizable for arbitrary couplings
- NLO will be discussed now

$\rightarrow$ more general ansatz

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This was used in Chiral Perturbation Theory (χPT)

$$U \ \rightarrow \ lUr^\dagger, \qquad \text{where } l, r \in SU(2)_{L,R}$$

Effective Lagrangian at leading order

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- We identify $\frac{v^2}{\Lambda^2} \simeq \frac{1}{16\pi^2}$. $\longrightarrow$ $\Lambda \simeq 4\pi v \simeq 3\text{TeV}$

Power-counting

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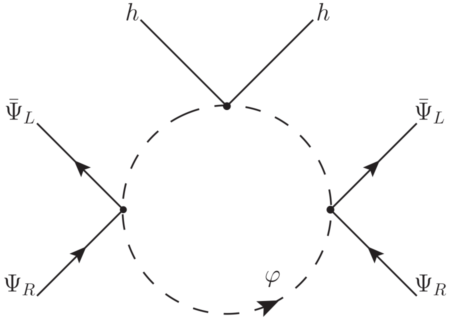

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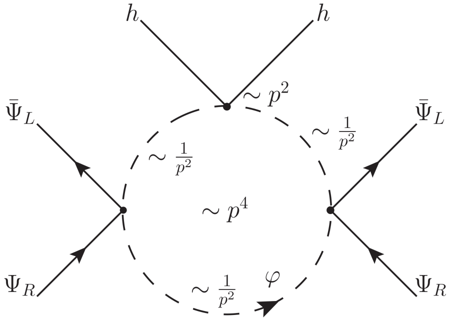

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$\rightarrow$ This allows a full classification of all NLO operators.

Power-counting

$$\mathcal{D} \sim p^{2L+2-X-\frac{1}{2}(F_L+F_R)-N_V} \left(\frac{\varphi}{v}\right)^B \left(\frac{h}{v}\right)^H \bar{\Psi}_L^{F_L^1} \Psi_L^{F_L^2} \bar{\Psi}_R^{F_R^1} \Psi_R^{F_R^2} \left(\frac{\mathcal{X}_{\mu\nu}}{v}\right)^X$$

define chiral dimensions with

$$2L+2 = d_p + X + \tfrac{1}{2}(F_L+F_R) + N_V$$

$$[\partial_\mu]_x = [D_\mu]_x = 1 \qquad [g]_x = [g']_x = 1 \qquad [y]_x = 1$$

$$[h\ ]_x = [U]_x = 0 \qquad [A]_x = [W]_x = [Z]_x = 0 \qquad [\Psi]_x = \tfrac{1}{2}$$

$\rightarrow$ This allows a full classification of all NLO operators.

Example:

$$\mathcal{O}_{D0,1} = \langle D_\mu U^\dagger D^\mu U\rangle \langle D_\nu U^\dagger D^\nu U\rangle\, \mathcal{F}\left(\tfrac{h}{v}\right)$$

$$[\mathcal{O}_{D0,1}]_x = 4 \longrightarrow \text{NLO}$$

Conclusions

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Effective Theories in general:

Applied to Higgs physics:

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Since we haven't seen any new physics at the LHC this is a very promising path of current research.

Backup

Example for operators

Classes of counterterms at 1 loop:

$$g^2 UD^2H, \quad UD^4H, \quad gUHXD^2, \quad g^2UHX^2,$$
$$y^2UHD\Psi^2, \quad yUHD^2\Psi^2, \quad ygUH\Psi^2X \text{ and } y^2\Psi^4UH.$$

For convenience we define:

$$L_\mu = iUD_\mu U^\dagger, \; \tau_L = UT_3U^\dagger,$$
$$P_\pm = \tfrac{1}{2} \pm T_3, \; P_{12} = T_1 + iT_2, \; P_{21} = T_1 - iT_2,$$
$$\eta = (\nu_R, e_R)^T \text{ and } r = (u_R, d_R)^T.$$

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$$\mathcal{O}_T = (gv)^2 \langle \tau_L L_\mu \rangle \langle \tau_L L^\mu \rangle \, \mathcal{F}$$

$\sum$: 1 operator

$$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1 \left(\frac{h}{v}\right) + a_2 \left(\frac{h}{v}\right)^2 + \ldots$$

$$\widetilde{\mathcal{F}}\left(\frac{h}{v}\right) = \widetilde{a}_1 \left(\frac{h}{v}\right) + \widetilde{a}_2 \left(\frac{h}{v}\right)^2 + \ldots$$

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$$\mathcal{O}_{D0,1} = \langle L_\mu L^\mu \rangle \langle L_\nu L^\nu \rangle \, \mathcal{F}$$

$$\mathcal{O}_{D1,4} = \langle L_\mu L_\nu \rangle \langle \tau_L L^\mu \rangle \left(\partial^\nu \frac{h}{v} \right) \, \mathcal{F}$$

$\sum$: 15 operators

$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1 \left(\frac{h}{v}\right) + a_2 \left(\frac{h}{v}\right)^2 + \ldots$

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$$\mathcal{O}_{XUD1} = g' \langle \tau_L L_\mu L_\nu \rangle B^{\mu\nu} \widetilde{\mathcal{F}}$$

$\sum$: 8 operators

$$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1 \left(\frac{h}{v}\right) + a_2 \left(\frac{h}{v}\right)^2 + \dots \qquad \widetilde{\mathcal{F}}\left(\frac{h}{v}\right) = \widetilde{a}_1 \left(\frac{h}{v}\right) + \widetilde{a}_2 \left(\frac{h}{v}\right)^2 + \dots$$

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$$\mathcal{O}_{XU1} = g'^2 B_{\mu\nu} B^{\mu\nu}\, \widetilde{\mathcal{F}}$$

$$\mathcal{O}_{XU9} = gg' B_{\mu\nu} \langle \tau_L W^{\mu\nu} \rangle\, \mathcal{F}$$

$\sum$: 10 operators

$$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \dots \qquad \widetilde{\mathcal{F}}\left(\frac{h}{v}\right) = \widetilde{a}_1\left(\frac{h}{v}\right) + \widetilde{a}_2\left(\frac{h}{v}\right)^2 + \dots$$

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$$\mathcal{O}_{\Psi V1} = y^2(\bar{q}\gamma^\mu q)\langle\tau_L L_\mu\rangle\,\mathcal{F}$$

$\sum$: 13 operators

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$$\mathcal{O}_{\Psi S1/2} = y\bar{q}UP_{\pm}r\langle L_\mu L^\mu\rangle\,\mathcal{F}$$

$$\mathcal{O}_{\Psi T1/2} = y\bar{q}\sigma_{\mu\nu}UP_{\pm}r\langle \tau_L L_\mu L_\nu\rangle\,\mathcal{F}$$

$\sum$: 28 operators + h.c.

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$$\mathcal{O}_{\Psi X 1/2} = yg' \bar{q}\sigma_{\mu\nu} UP_{\pm} rB^{\mu\nu}\, \mathcal{F}$$

$\sum$: 11 operators + h.c.

$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \dots$ $\qquad$ $\widetilde{\mathcal{F}}\left(\frac{h}{v}\right) = \widetilde{a}_1\left(\frac{h}{v}\right) + \widetilde{a}_2\left(\frac{h}{v}\right)^2 + \dots$

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$$\mathcal{O}_{LL1} = y^2(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu q)\,\mathcal{F}$$

$\sum$: 64 operators (+ h.c.)

$\mathcal{F}\left(\frac{h}{v}\right) = 1 + a_1\left(\frac{h}{v}\right) + a_2\left(\frac{h}{v}\right)^2 + \dots$ $\qquad$ $\widetilde{\mathcal{F}}\left(\frac{h}{v}\right) = \widetilde{a}_1\left(\frac{h}{v}\right) + \widetilde{a}_2\left(\frac{h}{v}\right)^2 + \dots$