Dimension-8 operators in Higgs physics

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22nd March 2018

Outline of this talk

1. Effective field theory
2. How to find ALL the operators
3. Some very basic phenomenology

Effective field theory

The Standard Model should be viewed as an *Effective Field Theory* (EFT).

$$\mathcal{L} = \sum_i \frac{c_i}{\Lambda_i^{d_i-4}} \mathcal{O}_i .$$

- Λ_i is a cutoff: the scale at which *new physics* appears which can contribute to $\mathcal{O}_i$.
- $\mathcal{O}_i$ are *all* possible operators consistent with Lorentz symmetry and gauge symmetries.
- c_i are the Wilson coefficients.

The "Standard Model" consists of operators with $d \leq 4$.

Dimension-5

At $d = 5$ we have an operator that can contribute to Majorana neutrino masses:

$$\mathcal{L}_5 = c_{\alpha\beta} \frac{(\overline{L}_\alpha^c H^*)(H^\dagger L_\beta)}{\Lambda}$$

For eV scale neutrino masses, we get $\Lambda \sim 10^{14}$ GeV.

Dimension-6 bosonic operators

Complete set of dim-6 operators involving Higgs and gauge bosons:

$$\mathcal{O}_H = \partial_\mu (H^\dagger H) \partial_\mu (H^\dagger H)$$
$$\mathcal{O}_W = (H^\dagger \tau^a D_\mu H) D_\nu W^a_{\mu\nu}$$
$$\mathcal{O}_{HW} = (D_\mu H^\dagger \tau^a D_\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_\gamma = (H^\dagger H) B_{\mu\nu} B_{\mu\nu}$$
$$\mathcal{O}_{cHW} = (D_\mu H^\dagger \tau^a D_\nu H) \widetilde{W}^a_{\mu\nu}$$
$$\mathcal{O}_{c\gamma} = (H^\dagger H) B_{\mu\nu} \widetilde{B}_{\mu\nu}$$

$$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\mathcal{O}_B = (H^\dagger \overleftrightarrow{D}_\mu H) \partial_\nu B_{\mu\nu}$$
$$\mathcal{O}_{HB} = (D_\mu H^\dagger D_\nu H) B_{\mu\nu}$$
$$\mathcal{O}_G = (H^\dagger H) G^a_{\mu\nu} G^a_{\mu\nu}$$
$$\mathcal{O}_{cHB} = (D_\mu H^\dagger D_\nu H) \widetilde{B}_{\mu\nu}$$

where $H^\dagger \overleftrightarrow{D}_\mu H = H^\dagger (D_\mu H) - (D_\mu H^\dagger) H$

If you write down *all* possible operators, not all will be independent. Operators can be related to one another by:

- Integration by parts: $\mathcal{O}_1 = \mathcal{O}_2 - D_\mu(\dots)$
- Equations of motion: $D_\mu D^\mu H = \dots$
- Fierz identities: $(D_\mu H^\dagger \tau^a D_\mu H)(H^\dagger \tau^a H) = \dots$

Why do we care about dimension-8 operators?

$$\sigma \propto \left(\mathrm{SM} + \frac{c_6}{\Lambda^2} + \frac{c_8}{\Lambda^4}\right)^2$$

- Dim-8 / SM interference terms appear at the same order as $\mathrm{dim}\text{-}6^2$ terms.
- Dim-8 operators should introduce an error on our bounds on dim-6 Wilson coefficients – but how big?
- In strongly coupled theories, dimension-8 terms may be more relevant.

The Hilbert series is a power series of invariants

$$\mathfrak{H} = \sum c_n t^n,$$

where t^n indicates invariants involving n objects t, and c_n is the number of independent invariants at that order.

HS at Dim-8 with 0 derivatives

Basic objects: H, $H^\dagger$, B_L, W_L, G_L.

$$\mathfrak{H} = (H^\dagger H)^4 + (H^\dagger H)^2 (B^L)^2 + (H^\dagger H)^2 \, B^L W^L +$$
$$2\,(H^\dagger H)^2\,(W^L)^2 + (H^\dagger H)^2 (G^L)^2 + (H^\dagger H) B^L (W^L)^2 +$$
$$(H^\dagger H)(W^L)^3 + (H^\dagger H)(G^L)^3.$$

L/R notation for gauge fields

$$SO(3,1) \to SO(4) \simeq SU(2)_L \times SU(2)_R$$

Field strength tensors $F_{\mu\nu}$ decompose as

$$(1,0) \oplus (0,1)$$

under $SU(2)_L \times SU(2)_R$.

Simpler to deal with $(1,0)$ and $(0,1)$ representations separately: $F^{L,R}_{\mu\nu}$.

$$F^{L,R}_{\mu\nu} = \frac{1}{2}(F_{\mu\nu} \pm i\widetilde{F}_{\mu\nu})$$

Dimension-8 operators with zero derivatives

$\mathcal{O}_1$	$(H^\dagger H)^4$	$\mathcal{O}_{10}$	$\epsilon_{IJK}\,(H^\dagger\tau^I H)B_{\mu\nu}W^J_{\nu\rho}W^K_{\rho\mu}$
$\mathcal{O}_2$	$(H^\dagger H)^2 B_{\mu\nu}B_{\mu\nu}$	$\mathcal{O}_{11}$	$\epsilon_{IJK}\,(H^\dagger\tau^I H)\left(\widetilde{B}_{\mu\nu}W^J_{\nu\rho}W^K_{\rho\mu} + B_{\mu\nu}W^J_{\nu\rho}\widetilde{W}^K_{\rho\mu}\right)$
$\mathcal{O}_3$	$(H^\dagger H)^2 B_{\mu\nu}\widetilde{B}_{\mu\nu}$	$\mathcal{O}_{12}$	$\epsilon_{IJK}\,(H^\dagger H)W^I_{\mu\nu}W^J_{\nu\rho}W^K_{\rho\mu}$
$\mathcal{O}_4$	$\delta_{IJ}\,(H^\dagger H)(H^\dagger\tau^I H)B_{\mu\nu}W^J_{\mu\nu}$	$\mathcal{O}_{13}$	$\epsilon_{IJK}\,(H^\dagger H)W^I_{\mu\nu}\widetilde{W}^J_{\nu\rho}W^K_{\rho\mu}$
$\mathcal{O}_5$	$\delta_{IJ}\,(H^\dagger H)(H^\dagger\tau^I H)B_{\mu\nu}\widetilde{W}^J_{\mu\nu}$	$\mathcal{O}_{14}$	$\delta_{AB}\,(H^\dagger H)^2 G^A_{\mu\nu}G^B_{\mu\nu}$
$\mathcal{O}_6$	$\delta_{IJ}(H^\dagger H)^2 W^I_{\mu\nu}W^J_{\mu\nu}$	$\mathcal{O}_{15}$	$\delta_{AB}\,(H^\dagger H)^2 G^A_{\mu\nu}\widetilde{G}^B_{\mu\nu}$
$\mathcal{O}_7$	$\delta_{IJ}(H^\dagger H)^2 W^I_{\mu\nu}\widetilde{W}^J_{\mu\nu}$	$\mathcal{O}_{16}$	$f_{ABC}\,(H^\dagger H)G^A_{\mu\nu}G^B_{\nu\rho}G^C_{\rho\mu}$
$\mathcal{O}_8$	$\delta_{IK}\delta_{JM}(H^\dagger\tau^I H)(H^\dagger\tau^J H)W^K_{\mu\nu}W^M_{\mu\nu}$	$\mathcal{O}_{17}$	$f_{ABC}\,(H^\dagger H)G^A_{\mu\nu}\widetilde{G}^B_{\nu\rho}G^C_{\rho\mu}$
$\mathcal{O}_9$	$\delta_{IK}\delta_{JM}(H^\dagger\tau^I H)(H^\dagger\tau^J H)W^K_{\mu\nu}\widetilde{W}^M_{\mu\nu}$		

Dimension-8 operators with two derivatives

$\mathcal{O}_{2D1}$	$(H^\dagger H)^2(D_\mu H^\dagger D_\mu H)$	$\mathcal{O}_{2D14}$	$i\,\epsilon_{IJK}\,(D_\mu H^\dagger\tau^I D_\nu H)(W^J_{\mu\rho}\widetilde{W}^J_{\rho\nu}+\widetilde{W}^J_{\mu\rho}W^K_{\rho\nu})$
$\mathcal{O}_{2D2}$	$\delta_{IJ}\,(H^\dagger H)(H^\dagger\tau^I H)(D_\mu H^\dagger\tau^J D_\mu H)$	$\mathcal{O}_{2D15}$	$\delta_{IJ}\,(D_\mu H^\dagger\,\tau^I D_\mu H)B_{\rho\sigma}W^J_{\rho\sigma}$
$\mathcal{O}_{2D3}$	$(D_\mu H^\dagger\,D_\nu H)B_{\mu\rho}B_{\rho\nu}$	$\mathcal{O}_{2D16}$	$\delta_{IJ}\,(D_\mu H^\dagger\,\tau^I D_\mu H)B_{\rho\sigma}\widetilde{W}^J_{\rho\sigma}$
$\mathcal{O}_{2D4}$	$(D_\mu H^\dagger D_\mu H)B_{\rho\sigma}B_{\rho\sigma}$	$\mathcal{O}_{2D17}$	$i\,\delta_{IJ}\,(D_\mu H^\dagger\tau^I D_\nu H)(B_{\mu\rho}W^J_{\rho\nu}-B_{\nu\rho}W^J_{\rho\mu})$
$\mathcal{O}_{2D5}$	$(D_\mu H^\dagger D_\mu H)B_{\rho\sigma}\widetilde{B}_{\rho\sigma}$	$\mathcal{O}_{2D18}$	$\delta_{IJ}\,(D_\mu H^\dagger\tau^I D_\nu H)(B_{\mu\rho}W^J_{\rho\nu}+B_{\nu\rho}W^J_{\rho\mu})$
$\mathcal{O}_{2D6}$	$\delta_{AB}\,(D_\mu H^\dagger D_\nu H)G^A_{\mu\rho}G^B_{\rho\nu}$	$\mathcal{O}_{2D19}$	$\delta_{IJ}\,(D_\mu H^\dagger\tau^I D_\nu H)(B_{\rho(\mu}\widetilde{W}^J_{\nu)\rho}-\widetilde{B}_{\rho(\mu}W^J_{\nu)\rho})$
$\mathcal{O}_{2D7}$	$\delta_{AB}\,(D_\mu H^\dagger D_\mu H)G^A_{\rho\sigma}G^B_{\rho\sigma}$	$\mathcal{O}_{2D20}$	$i\,\delta_{IJ}\,(D_\mu H^\dagger\tau^I D_\nu H)(B_{\rho\{\mu}\widetilde{W}^J_{\nu\}\rho}+\widetilde{B}_{\rho\{\mu}W^J_{\nu\}\rho})$
$\mathcal{O}_{2D8}$	$\delta_{AB}\,(D_\mu H^\dagger D_\mu H)G^A_{\rho\sigma}\widetilde{G}^B_{\rho\sigma}$	$\mathcal{O}_{2D21}$	$(H^\dagger H)(D_\mu H^\dagger\,D_\nu H)B_{\mu\nu}$
$\mathcal{O}_{2D9}$	$\delta_{IJ}\,(D_\mu H^\dagger D_\nu H)W^I_{\mu\rho}W^J_{\rho\nu}$	$\mathcal{O}_{2D22}$	$(H^\dagger H)(D_\mu H^\dagger\,D_\nu H)\widetilde{B}_{\mu\nu}$
$\mathcal{O}_{2D10}$	$\delta_{IJ}\,(D_\mu H^\dagger D_\mu H)W^I_{\rho\sigma}W^J_{\rho\sigma}$	$\mathcal{O}_{2D23}$	$\delta_{IJ}\,(H^\dagger H)(D_\mu H^\dagger\tau^I D_\nu H)W^J_{\mu\nu}$
$\mathcal{O}_{2D11}$	$\delta_{IJ}\,(D_\mu H^\dagger D_\mu H)W^I_{\rho\sigma}\widetilde{W}^J_{\rho\sigma}$	$\mathcal{O}_{2D24}$	$\delta_{IJ}\,(H^\dagger H)(D_\mu H^\dagger\tau^I D_\nu H)\widetilde{W}^J_{\mu\nu}$
$\mathcal{O}_{2D12}$	$i\,\epsilon_{IJK}\,(D_\mu H^\dagger\tau^I D_\nu H)W^J_{\mu\rho}W^K_{\rho\nu}$	$\mathcal{O}_{2D25}$	$\delta_{IJ}\,(H^\dagger\tau^I H)(D_\mu H^\dagger D_\nu H)W^J_{\mu\nu}$
$\mathcal{O}_{2D13}$	$\epsilon_{IJK}\,(D_\mu H^\dagger\tau^I D_\nu H)(W^J_{\mu\rho}\widetilde{W}^K_{\rho\nu}-\widetilde{W}^J_{\mu\rho}W^K_{\rho\nu})$	$\mathcal{O}_{2D26}$	$\delta_{IJ}\,(H^\dagger\tau^I H)(D_\mu H^\dagger D_\nu H)\widetilde{W}^J_{\mu\nu}$

Field redefinitions

When the Higgs gets a VEV, higher dimensions operators lead to corrections to kinetic terms. For example

$$(H^\dagger H)B_{\mu\nu}B^{\mu\nu} \to v^2 B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{L}_B = \left(1 + \frac{c_\gamma v^2}{\Lambda^2} + \dots\right) B_{\mu\nu}B^{\mu\nu}$$

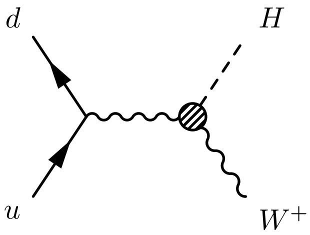
Field redefinition:

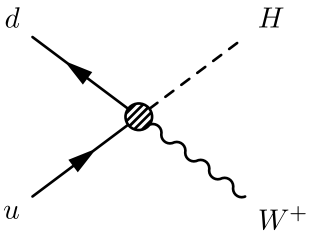
$$B_\mu \to \left(1 - \frac{1}{2}\frac{c_\gamma v^2}{\Lambda^2} + \dots\right) B_\mu$$

At dim-8 we will get corrections $\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$.

Probing the EFT

We can probe a subset of these operators via processes such as $pp \to HW$:

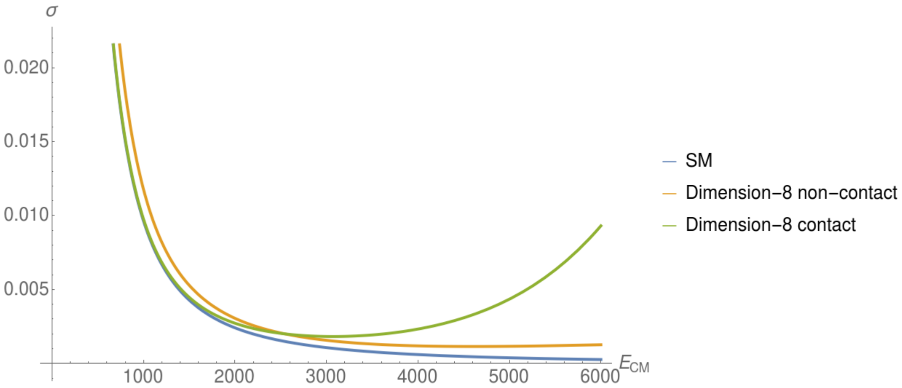




Also need to consider 'contact' operators involving fermions, e.g.

$$(\overline{Q}_L \sigma_\mu Q_L)(H^\dagger \tau^a \overleftrightarrow{D}_\nu H) W^a_{\mu\nu}$$

Cross section dependence



Contribution to cross-section from contact operators grows very rapidly with COM energy $\sim E_{CM}^6$

Conclusions

- In the absence of direct detection of new physics, we must treat the Standard Model as an EFT.
- To this end, we have contributed a complete set of bosonic dimension-8 operators.
- In order to apply to specific process, must consider fermionic contact operators as well.

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Thanks for your attention!