Dimension-8 Operators in VBS

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Motivation

Vector-Boson Scattering as considered process

Look for possible deviations from SM
Assumption: new physics heavy $\rightarrow$ SM + effective vertices

Which vertices?

- $ffV \rightarrow V$ decays
- $ffff \rightarrow$ 4-fermion contact interaction
- $VVV \rightarrow$ diboson production
- ...

better sensitivity in other channels with larger cross sections

remaining vertex:

- $VVVV \leftrightarrow$ triboson production

Motivation

How to generate $VVVV$ from EFT?

(linear) EFT building blocks

- Higgs doublet field Φ
- covariant derivative D^μ, which reduces to ∂^μ for singlet fields
- field strength tensors $G^{a,\mu\nu}$, $W^{i,\mu\nu}$, $B^{\mu\nu}$
- fermion fields ψ

combinations to get V (all dimension-2):

- $D^\mu\Phi$
- $W^{i,\mu\nu}$ (also non-abelian part containing VV)
- $B^{\mu\nu}$

$\Rightarrow$ lowest-order contribution: dimension-6

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right]$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger\,\widehat{W}^{\mu\nu}\,(D_\nu\Phi)$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}\left[\widetilde{\widehat{W}}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right]$$

Motivation

⇒ lowest-order contribution: dimension-6

	$\mathcal{O}_{WWW}$	$\mathcal{O}_{W}$	$\mathcal{O}_{B}$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{\phi,2}$	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\widetilde{W}}$	$\mathcal{O}_{\widetilde{B}}$	$\mathcal{O}_{\widetilde{W}W}$	$\mathcal{O}_{\widetilde{B}B}$
WWZ	X	X	X				X	X	X		
$WW\gamma$	X	X	X				X	X	X		
HWW		X		X		X		X		X	
HZZ		X	X	X	X	X		X	X	X	X
$HZ\gamma$		X	X	X	X	(X)		X	X	X	X
$H\gamma\gamma$				X	X	(X)				X	X
$WWWW$	X	X					X				
$WWZZ$	X	X					X				
$WWZ\gamma$	X	X					X				
$WW\gamma\gamma$	X						X				

⇒ also give contributions to *VVV* vertices

⇒ test in diboson production

severely constrained (parametric uncertainty relevant? → task)

⇒ look at next order of expansion

→ dimension-8

dimension-6 contribution could be loop-induced [Arzt, Einhorn, Wudka]
→ additional factor $\frac{1}{16\pi^2} \sim \frac{1}{160}$
if dimension-8 tree-level → similar size of effects possible

Dimension-8

Bosonic dimension-8 operators

[Eboli, Gonzalez-Garcia]

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,2} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{O}_{M,3} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu\Phi\right] \times \widehat{B}^{\beta\nu}$$

$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu\Phi\right] \times \widehat{B}^{\beta\mu}$$

$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right]$$

$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$

$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right]$$

$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$

$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu}$$

$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$

$$\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$

$$\mathcal{O}_{T,9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$

Dimension-8

Hiccups of the original version:

vanish identically:

$$\mathcal{O}_{T,3} = \text{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\widehat{W}^{\nu\alpha}\right] \times \widehat{B}_{\beta\nu}$$
$$\mathcal{O}_{T,4} = \text{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\alpha\mu}\widehat{W}^{\beta\nu}\right] \times \widehat{B}_{\beta\nu}$$

redundant:

$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger \widehat{W}_{\beta\nu}\widehat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$= \frac{1}{2}\mathcal{O}_{M,0}$$

missing:

$$\mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

Dimension-8

Contribution to the different vertices:

	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$
$WWWW$	X	X		X		
$WWZZ$	X	X	X	X	X	
$ZZZZ$	X	X	X	X	X	X
$WWZ\gamma$		X	X	X	X	
$WW\gamma\gamma$		X	X	X	X	
$ZZZ\gamma$		X	X	X	X	X
$ZZ\gamma\gamma$		X	X	X	X	X
$Z\gamma\gamma\gamma$				X	X	X
$\gamma\gamma\gamma\gamma$				X	X	X

Defining the field-strength tensors

For dimension-6 operators, typically field-strength tensors slightly modified

$$\widehat{W}^{\mu\nu} = ig\frac{\sigma^j}{2}W^{j,\mu\nu} = ig\frac{\sigma^j}{2}\left(\partial^\mu W^{j,\nu} - \partial^\nu W^{j,\mu} - g\epsilon^{jkl}W^{k,\mu}W^{l,\nu}\right)$$

$$\widehat{B}^{\mu\nu} = ig'\frac{1}{2}B^{\mu\nu} = ig'\frac{1}{2}\left(\partial^\mu B^\nu - \partial^\nu B^\mu\right)$$

such that

$$[D^\mu, D^\nu] = \widehat{W}^{\mu\nu} + \widehat{B}^{\mu\nu}$$

$\rightarrow$ treated on equal footing with covariant derivative
(used in VBFNLO for both dim-6 and dim-8)

[Eboli, Gonzalez-Garcia] (also MadGraph/UFO implementation):

$$\widehat{W}^{\mathrm{EGM},\mu\nu} = \frac{\sigma^j}{2}W^{j,\mu\nu} = \frac{\sigma^j}{2}\left(\partial^\mu W^{j,\nu} - \partial^\nu W^{j,\mu} - g\epsilon^{jkl}W^{k,\mu}W^{l,\nu}\right)$$

$$\widehat{B}^{\mathrm{EGM},\mu\nu} = B^{\mu\nu} = \left(\partial^\mu B^\nu - \partial^\nu B^\mu\right)$$

resulting in

$$\widehat{W}^{\mathrm{EGM},\mu\nu} = \frac{1}{ig}\widehat{W}^{\mu\nu} \qquad \widehat{B}^{\mathrm{EGM},\mu\nu} = \frac{2}{ig'}\widehat{B}^{\mu\nu}$$

Non-linear EFT

Also possible to use non-linear EFT (electroweak chiral Lagrangian)

$$\mathcal{L}_4 = \alpha_4 \left(\mathrm{Tr}\left[V_\mu V_\nu\right]\right)^2 ,$$
$$\mathcal{L}_5 = \alpha_5 \left(\mathrm{Tr}\left[V_\mu V^\mu\right]\right)^2 ,$$

$$\mathcal{L}_{S,0} = F_{S,0}\, \mathrm{Tr}\left[(D_\mu \hat{H})^\dagger D_\nu \hat{H}\right] \times \mathrm{Tr}\left[(D^\mu \hat{H})^\dagger D^\nu \hat{H}\right] ,$$
$$\mathcal{L}_{S,1} = F_{S,1}\, \mathrm{Tr}\left[(D_\mu \hat{H})^\dagger D^\mu \hat{H}\right] \times \mathrm{Tr}\left[(D_\nu \hat{H})^\dagger D^\nu \hat{H}\right] .$$

with

$$V_\mu = \Sigma\,(D_\mu \Sigma)^\dagger = -\,(D_\mu \Sigma)\,\Sigma^\dagger ,$$
$$D_\mu \Sigma = \partial_\mu \Sigma + ig\frac{\sigma^a}{2} W^a_\mu \Sigma - ig' \Sigma B_\mu \frac{\sigma^3}{2} ,$$
$$\Sigma = \exp\left(-\frac{i}{v}\sigma^a w^a\right) \overset{\text{unitary gauge}}{=} 1$$
$$\hat{H} = \frac{1}{2}\begin{pmatrix} v + H - iw^3 & -i(w^1 - iw^2) \\ -i(w^1 + iw^2) & v + H + iw^3 \end{pmatrix} \overset{\text{unitary gauge}}{=} \frac{v + H}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$\rightarrow$ Whizard

Relation to linear EFT

Relations between linear and non-linear EFT

$$\alpha_4 = \frac{v^4}{16} F_{S,0} = \frac{v^4}{16} \frac{f_{S,0} + f_{S,2}}{\Lambda^4} \,, \qquad f_{S,0} = f_{S,2}$$

$$\alpha_5 = \frac{v^4}{16} F_{S,1} = \frac{v^4}{16} \frac{f_{S,1}}{\Lambda^4}$$

Linear-EFT scenarios with $f_{S,0} \neq f_{S,2}$ need additional operator

$$\mathcal{L}_6 = \alpha_6 \, \mathrm{Tr}\left[V_\mu V_\nu\right] \mathrm{Tr}\left[T V^\mu\right] \mathrm{Tr}\left[T V^\nu\right]$$

with $T = \Sigma \sigma_3 \Sigma^\dagger$

isospin-breaking

Conclusions

Karlsruhe Institute of Technology

- parametrization of effects contributing to *VVVV* vertex

- effects not constrained by other, ”easier” measurements

  $\rightarrow$ dimension-8

  (possibly leading tree-level contribution of new physics)

  $\leftrightarrow$ impact of dimension-6 operators taken at limits?

- subtle convention differences in implementations

  $\rightarrow$ unified definitions?

  ($\leftrightarrow$ subtle Snowmass 2013 hint [arXiv:1309.7890] not picked up by experiments)

more detailed write-up: [MR, arXiv:1610.08420]

Backup

Dimension-6 operators

$$\mathcal{O}_{WWW} = \text{Tr}\left[\widehat{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right] ,$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger\, \widehat{W}^{\mu\nu}\, (D_\nu\Phi) ,$$

$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger\, \widehat{B}^{\mu\nu}\, (D_\nu\Phi) ,$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi ,$$

$$\mathcal{O}_{BB} = \Phi^\dagger \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi ,$$

$$\mathcal{O}_{\phi,2} = \partial_\mu \left(\Phi^\dagger\Phi\right) \partial^\mu \left(\Phi^\dagger\Phi\right) ,$$

$$\mathcal{O}_{\widetilde{W}WW} = \text{Tr}\left[\widetilde{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right] ,$$

$$\mathcal{O}_{\widetilde{W}} = (D_\mu\Phi)^\dagger\, \widetilde{W}^{\mu\nu}\, (D_\nu\Phi) ,$$

$$\mathcal{O}_{\widetilde{B}} = (D_\mu\Phi)^\dagger\, \widetilde{B}^{\mu\nu}\, (D_\nu\Phi) ,$$

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi ,$$

$$\mathcal{O}_{\widetilde{B}B} = \Phi^\dagger \widetilde{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi .$$

Deviation Patterns

Can we say something about size of EFT coefficients? [Arzt, Einhorn, Wudka hep-ph/9405214]

- Assumption: high-energy theory (HET) is gauge theory
- keep track of *all* possible operators $\rightarrow$ a priori no EOM
- statement can be HET-dependent $\rightarrow$ take maximum contribution

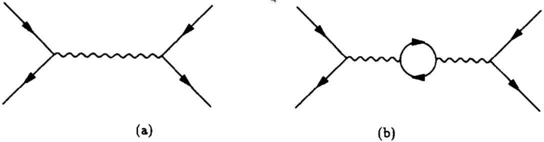

Fig. 1. The contributions of two types of underlying physics to the four-fermion operator. (a) A heavy gauge boson leads to an effective coupling of order one. (b) A heavy fermion comes in only at the one-loop level and leads to an effective coupling of order $1/16\pi^2$.

- $\rightarrow$ list of all possible dim-$\leq$ 6 graphs from power-counting
- gauge theory restricts structure of vertices
  e.g. vector interactions: from $F_a^{\mu\nu} F^a_{\mu\nu}$ terms in $\mathcal{L}$
  group structure $\rightarrow$ only *AAAA*, *XXXX*, *AAXX*, *AXXX* vertices (*A* SM-*V*, *X* NP-*V*)
- $\rightarrow$ basis splitting into tree-level and loop-induced
- dim-8 operators of *VVV* can be as large as dim-6

Deviation Patterns (2)

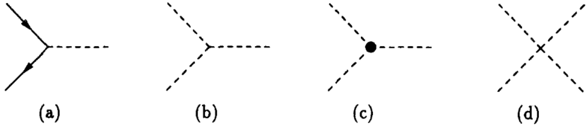

Fig. 2. These are all possible relevant vertices in an unconstrained field theory. Each dashed line may be a scalar or a vector. The dot represents a coupling constant proportional to Λ, the heavy scale.

In summary, the forbidden vertices are

$$\phi_{\mathrm{li}}\phi_{\mathrm{li}}\phi_{\mathrm{li}}, \quad \phi_{\mathrm{li}}\phi_{\mathrm{h}}AA, \quad \phi_{\mathrm{li}}\phi_{\mathrm{h}}A, \quad \phi_{\mathrm{li}}AX,$$
$$\phi_{\mathrm{li}}AA, \quad \phi_{\mathrm{h}}AA, \quad \phi_{\mathrm{h}}AX, \quad \phi_{\mathrm{li}}XX,$$
$$AAX, \quad AAAX, \quad \psi_{\mathrm{li}}\psi_{\mathrm{h}}A.$$

Deviation Patterns (3)

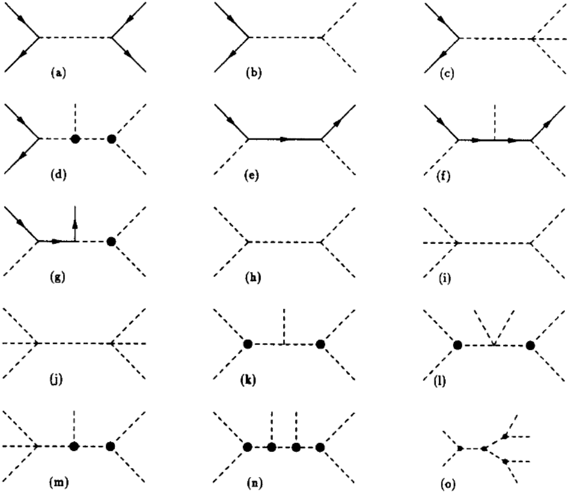

Fig. 3. These are all possible tree graphs which are suppressed by at most $1/\Lambda^2$, in a general field theory, with only heavy internal lines and light external lines. The dotted three-boson vertices must have a coupling constant proportional to Λ, the heavy mass scale. Each dashed line may be a scalar or a vector.