Karlsruhe Institute of Technology

EFT in VBF and VBS

Michael Rauch | HL-/HE-LHC Workshop, 31 Oct 2017

INSTITUTE FOR THEORETICAL PHYSICS

Motivation

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- Vector-Boson Fusion (VBF) and Vector-Boson Scattering (VBS) important processes for HL-/HE-LHC [→ talks by Jan Kieseler, Claire Lee]
- searches for new physics important task
- useful tool for heavy new physics: effective field theory (EFT)

  assumption: new physics is heavy
  can integrate out heavy, non-SM degrees of freedom
  higher-dimensional operators appearing in Lagrangian

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_{i} \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

  - operators $\mathcal{O}$ contain SM fields only
  - respect SM gauge symmetries
  - suppressed by $1/\Lambda^{d-4}$ (Λ: scale of new physics)
    → keep only leading order(s) (lowest dimension $d = 6$)
  - building blocks:
    - Higgs field Φ
    - (covariant) derivative ∂^μ, D^μ
    - field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$
    - fermion fields ψ

Linear Lagrangian

- linear realization of the EFT [Buchmüller, Wyler; Hagiwara et al; Grzadkowski et al; . . .]
- D6: 59 operators when assuming
  - baryon/lepton-number conservation
  - flavour universality

List of Operators (only gauge and Higgs couplings)

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \widehat{W}^{\mu\nu} \, (D_\nu \Phi) \qquad \mathcal{O}_B = (D_\mu \Phi)^\dagger \, \widehat{B}^{\mu\nu} \, (D_\nu \Phi)$$

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

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^{\mu}{}_{\nu} \widehat{W}^{\nu}{}_{\rho} \widehat{W}^{\rho}{}_{\mu}\right] \qquad \mathcal{O}_{\phi,2} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$$

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

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

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

One constraint on CP-odd operators

$$\mathcal{O}_{\widetilde{W}} + \frac{1}{2}\mathcal{O}_{\widetilde{W}W} = \mathcal{O}_{\widetilde{B}} + \frac{1}{2}\mathcal{O}_{\widetilde{B}B}$$

Additional CP-even operator

$$\mathcal{O}_{\phi W} = \mathrm{Tr}\left[W^{\mu\nu} W_{\mu\nu}\right] \Phi^\dagger \Phi \equiv 2\mathcal{O}_{WW}$$

Vertex Contributions

List of Operators (only gauge and Higgs couplings)

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \widehat{W}^{\mu\nu} \, (D_\nu \Phi) \qquad \mathcal{O}_B = (D_\mu \Phi)^\dagger \, \widehat{B}^{\mu\nu} \, (D_\nu \Phi)$$

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

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^{\mu}{}_{\nu} \widehat{W}^{\nu}{}_{\rho} \widehat{W}^{\rho}{}_{\mu}\right] \qquad \mathcal{O}_{\phi,2} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$$

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

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

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

Modification of corresponding triple-gauge-coupling vertices:

	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{\phi,2}$	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\widetilde{W}}$	$\mathcal{O}_{\widetilde{B}}$	$\mathcal{O}_{\widetilde{W}W}$	$\mathcal{O}_{\widetilde{B}B}$
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				

Dimension-8

Bosonic dimension-8 operators [Eboli, Gonzalez-Garcia]

(D6 could be loop-induced → D8 effects can become sizable [Arzt, Einhorn, Wudka])

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

→ each operators contains at least four bosons

⇒ leading contribution to quartic gauge coupling

Non-linear EFT

Also possible to use non-linear EFT (electroweak chiral Lagrangian) based on power counting in terms of canonical dimension

[Appelquist; Longhitano; . . . ; Alboteanu, Kilian, Reuter; . . .]

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

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

with

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

Experimental Projections

Some projection studies available for HL-LHC [↔ talk by Claire Lee]

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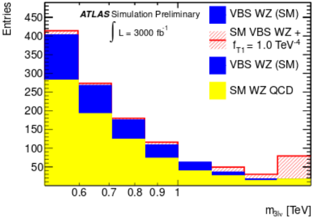
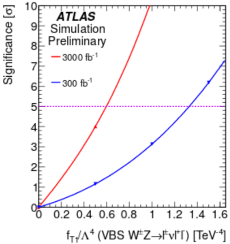
ATLAS:





Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

CMS (*WZjj*):

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

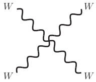
→ test energy scales up to

- $f = 4\pi$: $\Lambda = 2.5$ TeV
- $f = 1$: $\Lambda = 1.4$ TeV
- $f = \frac{1}{16\pi^2}$: $\Lambda = 0.4$ TeV

Unitarity Violation

Important gauge cancellations between different diagram types

- longitudinal W scattering through quartic gauge boson vertex



high energy limit: centre-of-mass energy $\sqrt{s} \to \infty$

$\mathcal{M}_{\text{quartic vertex}} \propto s^2 \quad \to$ cross section diverges $\quad \sigma \propto s^4/s = s^3 \to \infty$

Gauge boson with momentum $\vec{p} = (0,0,p)^T$:

longitudinal polarization vector:

$$\epsilon_L^\mu = \frac{1}{M}(p,0,0,E)^T \overset{E \gg M}{=} \frac{p^\mu}{M}$$

Unitarity Violation

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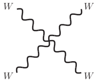
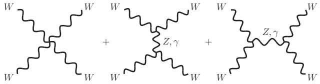


high energy limit: centre-of-mass energy $\sqrt{s} \to \infty$
$\mathcal{M}_{\text{quartic vertex}} \propto s^2 \quad \to$ cross section diverges $\quad \sigma \propto s^4/s = s^3 \to \infty$

- add triple gauge boson vertices

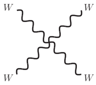


$\mathcal{M}_{\text{quartic+triple vertices}} \propto s \to$ still divergent

Unitarity Violation

Important gauge cancellations between different diagram types

- longitudinal W scattering through quartic gauge boson vertex



high energy limit: centre-of-mass energy $\sqrt{s} \to \infty$

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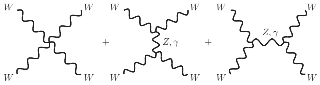
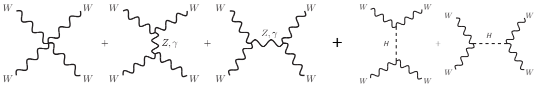
- add triple gauge boson vertices



$\mathcal{M}_{\text{quartic+triple vertices}} \propto s \to$ still divergent

- additional Higgs diagrams



remove divergence exactly $\quad \mathcal{M} \propto$ const. $\quad \sigma \propto 1/s \to 0$

Anomalous gauge couplings spoil cancellation → stringent tests

Unitarization

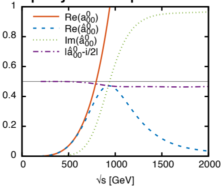
Anomalous gauge couplings spoil cancellation
$\leftrightarrow$ effects can become large $\rightarrow$ unitarity violation $\rightarrow$ unphysical

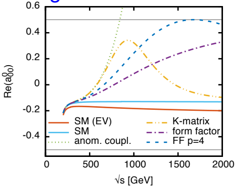
Several solutions:

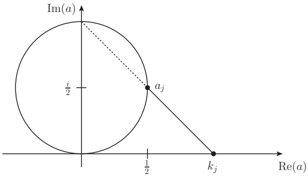
- consider only unitarity-conserving phase-space regions [. . .]
  loses some information $\rightarrow$ possibly reduced sensitivity
  cut on relevant region might not be directly accessible ($m_{4\ell}$ vs. neutrinos)
- (dipole) form factor multiplying amplitudes

$$\mathcal{F}(s) = \frac{1}{\left(1 + \frac{s}{\Lambda_{\mathrm{FF}}^2}\right)^n} \qquad \Lambda_{\mathrm{FF}}^2,\ n\text{: free parameters}$$

- K-/T-matrix unitarization [Alboteanu, Kilian, Reuter, Sekulla]
  based on partial-wave analysis [Jacob, Wick]
  project amplitude back onto Argand circle



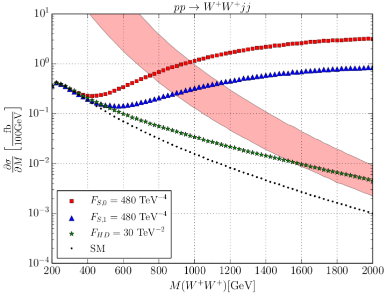




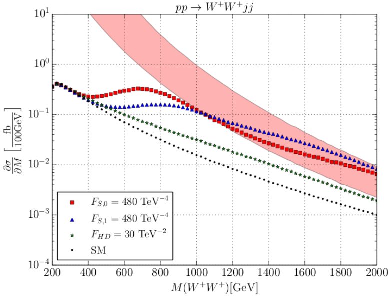
Unitarization

[Sekulla (Whizard)]

no unitarization



T-matrix unitarization



red band: one/all partial-wave amplitudes saturated

Impact of Current Limits

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Investigate impact of D6 vs D8 operators on VBS

D6 input: Global Higgs and Gauge analysis of run-I data

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]

Take results and apply to vector-boson scattering

$\Rightarrow$ No contribution from $\mathcal{O}_{GG}$ and fermionic operators

$f_x/\Lambda^2[\mathrm{TeV}^{-2}]$	LHC–Higgs + LHC–TGV + LEP–TGV Best fit	95% CL interval
f_{WW}	-0.1	$(-3.1, 3.7)$
f_{BB}	0.9	$(-3.3, 6.1)$
f_W	1.7	$(-0.98, 5.0)$
f_B	1.7	$(-11.8, 8.8)$
f_{WWW}	-0.06	$(-2.6, 2.6)$
$f_{\phi,2}$	1.3	$(-7.2, 7.5)$

For simplicity: use pos. and neg. 95% CL bound with other parameters set to zero
$\rightarrow$ slightly larger effect than true 95% CL bound

Additionally:

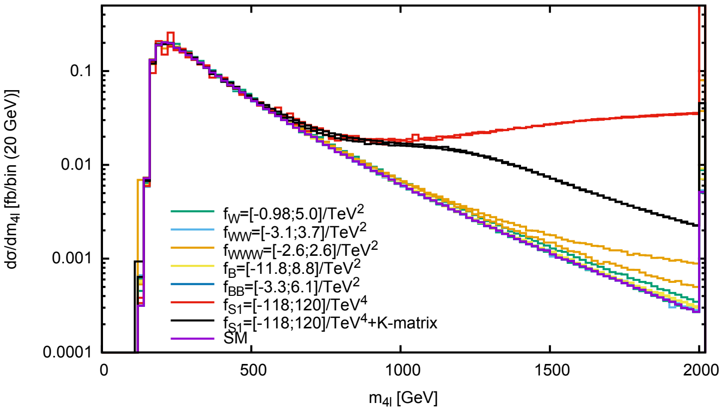
effect from dimension-8 operator $\mathcal{O}_{S,1}$

using CMS, $W^\pm W^\pm jj$, $\sqrt{S} = 8$ TeV, no unitarization [arXiv:1410.6315]

$$f_{S,1}/\Lambda^4 \in (-118, 120)\mathrm{TeV}^{-4} \qquad (\text{for } f_{S,0}/\Lambda^4 = 0)$$

Results

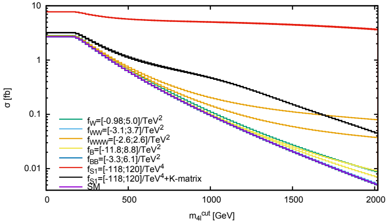
Process: $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$, $\sqrt{S} = 13$ TeV, VBF cuts, NLO QCD

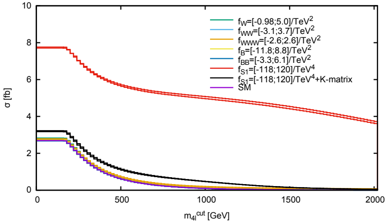


- last bin: overflow bin, $m_{4\ell} > 2000$ GeV
- effect of D6 contributions in general small; largest one by $\mathcal{O}_{WWW}$
- D8 operator clearly dominating

Process: $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$, $\sqrt{S} = 13$ TeV, VBF cuts, NLO QCD

cross section when requiring $m_{4\ell} > m_{4\ell}^{\text{cut}}$





- $\mathcal{O}_{WWW}$ contribution large only for very high $m_{4\ell} \leftrightarrow$ low event counts

  excess of 10 events for $m_{4\ell} > 1$ TeV, $\mathcal{L} = 100$ fb^{-1}, SM contrib. of 10 events
  other D6 operators below 1 event

  $\leftrightarrow$ unitarity violating contributions (?)

- $\mathcal{O}_{S1}$ yielding large excess even without cuts on $m_{4\ell}$

  excess of almost 500 events for $m_{4\ell} > 1$ TeV, $\mathcal{L} = 100$ fb^{-1}
  even after unitarization excess of 37 events

Conclusions & Open Tasks

- EFT formulation useful tool to parametrize new-physics

- contribution to anomalous triple and quartic gauge couplings

- strong growth with energy
  $\rightarrow$ unitarity violation in experimentally probed region
  $\Rightarrow$ need some mitigation procedure (cut, form factor, T-matrix, . . .)

- effect of dimension-6 operators in VBF/VBS processes in general small
  13/14 TeV diboson data will further reduce the allowed contributions
  final accuracy vs effects in VBF/VBS

- effect of dimension-8 operators dominates
  $\rightarrow$ constraining power of experimental results
  $\rightarrow$ expectations for HE-LHC

Backup

Dimension-8

Hiccups of the original version:

vanish identically:

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

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

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

Relation non-linear to linear EFT

Relations between linear and non-linear EFT

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

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

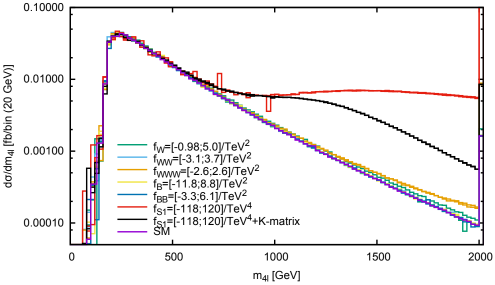
Linear-EFT scenarios with $f_{S,0} \neq f_{S,2}$ need additional operator

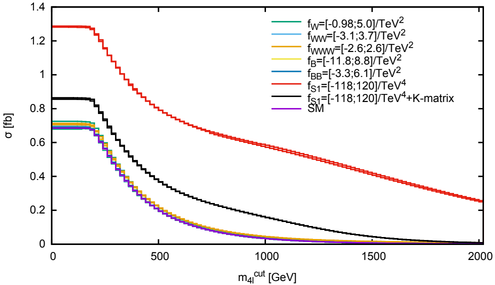
$$\mathcal{L}_6 = \alpha_6 \,\mathrm{Tr}\,[V_\mu V_\nu]\,\mathrm{Tr}\,[TV^\mu]\,\mathrm{Tr}\,[TV^\nu]$$

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

isospin-breaking

Results





Process:
$pp \to W^+Zjj$
$\to \ell^+\nu\ell^+\ell^- jj$,
$\sqrt{S} = 13$ TeV, VBF cuts,
NLO QCD

exactly the same picture as in W^+W^+jj case