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Effect of Dimension-6 Operators on VBS

Michael Rauch | VBSCAN WG1 Vidyo meeting, 21 Sep 2017

INSTITUTE FOR THEORETICAL PHYSICS

Motivation

- searches for new physics heavily ongoing in both ATLAS and CMS
- useful tool for heavy new physics: effective field theory (EFT)

  integrate out heavy, non-SM degrees of freedom
  higher-dimensional operators appearing in Lagrangian

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

  $\rightarrow$ lowest relevant order: $d = 6$ (D6)

- effects from D6 operators also appear in processes with larger cross sections
  $\rightarrow$ higher statistics
  $\rightarrow$ smaller errors
- $\Rightarrow$ investigate impact of these constraints

Setup

- linear realization of the EFT
- D6: 59 operators when assuming
  - baryon/lepton-number conservation
  - flavour universality
- further restrictions: [Corbett et al.]
  - P and C–even operators
  - no operators contributing to EW precision observables at tree level
  - no operators where data is lacking (e.g. HHH coupling)

List of Operators

$$\mathcal{O}_{GG} = \phi^\dagger \phi \; G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi$$

$$\mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$$

$$\mathcal{O}_{e\phi,33} = (\phi^\dagger \phi)(\bar{L}_3 \phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \tilde{\phi} u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \phi d_{R,3})$$

$$\mathcal{O}_{WWW} = \mathrm{Tr} \left(\hat{W}^\mu{}_\nu \hat{W}^\nu{}_\rho \hat{W}^\rho{}_\mu \right)$$

Vertex Contributions

List of Operators

$$\mathcal{O}_{GG} = \phi^\dagger \phi \, G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi$$

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$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}^\mu{}_\nu \hat{W}^\nu{}_\rho \hat{W}^\rho{}_\mu\right)$$

Modification of corresponding TGV vertices:

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

Measurements

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

Global fit of these operators to available ATLAS, CMS & LEP data
(LHC: run-I measurements)

Higgs data

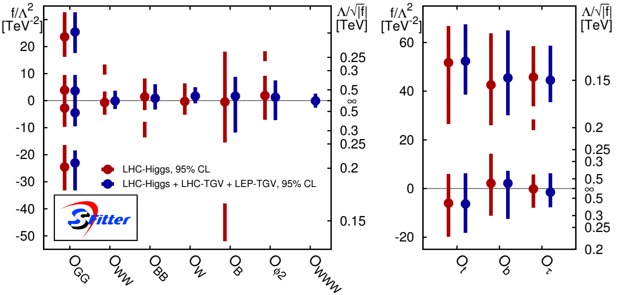
production/decay mode	ATLAS	CMS
$H \to WW$	1412.2641	1312.1129
$H \to ZZ$	1408.5191	1312.5353
$H \to \gamma\gamma$	1408.7084	1407.0558
$H \to \tau\bar{\tau}$	1501.04943	1401.5041
$H \to b\bar{b}$	1409.6212	1310.3687
$H \to Z\gamma$	ATLAS-CONF-2013-009	1307.5515
$t\bar{t}H$ production	1408.7084, 1409.3122	1407.0558,1408.1682,1502.02485
kinematic distributions	1409.6212,1407.4222	

Gauge boson data

Channel	Distribution	Data set	Reference
$WW \to \ell^+\ell'^- + \not{E}_T$ (0j)	Leading lepton p_T	ATLAS 8 TeV, 20.3 fb^{-1}	1603.01702
$WW \to \ell^+\ell^{(\prime)-} + \not{E}_T$ (0j)	$m_{\ell\ell^{(\prime)}}$	CMS 8 TeV, 19.4 fb^{-1}	1507.03268
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	ATLAS 8 TeV, 20.3 fb^{-1}	1603.02151
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	CMS 8 TeV, 19.6 fb^{-1}	CMS-PAS-SMP-12-006
$WV \to \ell^\pm jj + \not{E}_T$	V candidate p_T^{jj}	ATLAS 7 TeV, 4.6 fb^{-1}	1410.7238
$WV \to \ell^\pm jj + \not{E}_T$	V candidate p_T^{jj}	CMS 7 TeV, 5.0 fb^{-1}	1210.7544
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	ATLAS 7 TeV, 4.6 fb^{-1}	1208.1390
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	CMS 7 TeV, 4.9 fb^{-1}	CMS-PAS-SMP-12-006

Fit Results

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



f_x/Λ^2 [TeV^{-2}]	LHC–Higgs + LHC–TGV + LEP–TGV	
	Best fit	95% CL interval
f_{GG}	-4.5	$(-9.5, 9.5)$
f_{WW}	-0.1	$(-3.1, 3.7)$
f_{BB}	0.9	$(-3.3, 6.1)$
$f_{\phi,2}$	1.3	$(-7.2, 7.5)$
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_b	2.2	$(-12.5, 7.3)$
f_τ	-1.5	$(36, 59)$
f_t	-6.3	$(39, 68)$

Towards VBS

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Take results and apply to vector-boson scattering

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

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

$f_x/\Lambda^2[\text{TeV}^{-2}]$	LHC–Higgs + LHC–TGV + LEP–TGV Best fit	95% CL interval
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$f_{\phi,2}$	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:

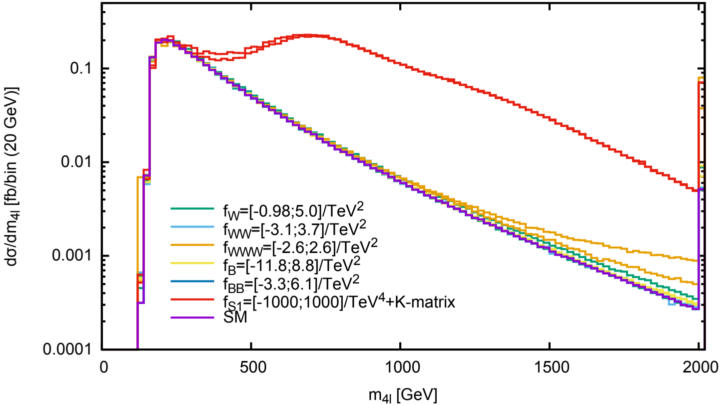
effect from dimension-8 operator $\mathcal{O}_{S,1}$

using ATLAS, $W^\pm W^\pm jj$, $\sqrt{S} = 8$ TeV, K-matrix unitarization [arXiv:1405.6241]

$$f_{S,1}/\Lambda^4 \in (-1000, 1000)\text{TeV}^{-4} \qquad (\text{for } f_{S,0}/\Lambda^4 = 0)$$

Results

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

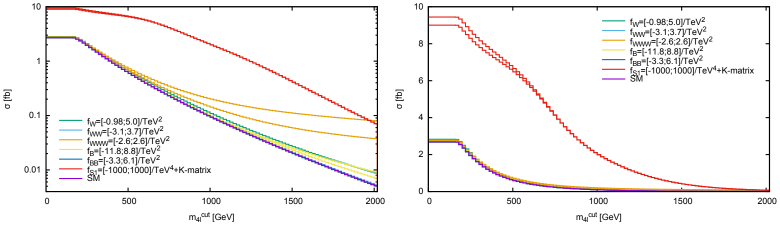


- last bin: overflow bin, $m_{4\ell} > 2000$ GeV
- effect of D6 contributions in general small; largest one by $\mathcal{O}_{WWW}$
- D8 operator clearly dominating

Results

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 200 events for $m_{4\ell} > 1$ TeV, $\mathcal{L} = 100$ fb^{-1}

Results

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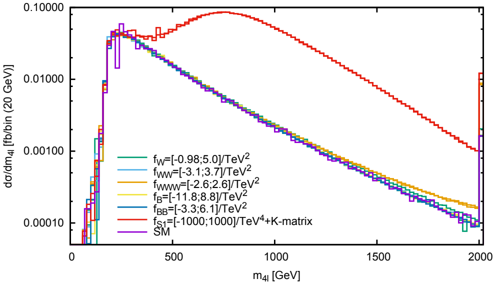

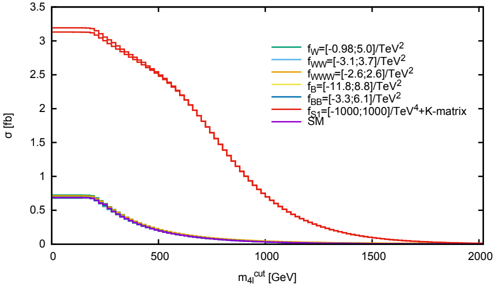

Process:
$pp \to W^+Zjj$
$\to \ell^+\nu\ell^+\ell^- jj$,
$\sqrt{S} = 13$ TeV, VBF cuts,
NLO QCD

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

Conclusions

- study impact of dimension-6 and dimension-8 operators on VBS

  take 95%CL bounds from LHC run-I results
  show impact on 13 TeV VBS cross section

- effect of dimension-6 operators in general small

  13 TeV diboson data will further reduce the allowed contributions

- effect of dimension-8 operators dominates

  $\rightarrow$ constraining power of experimental results

Backup

Dimension-6 operators

$$
\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}\left[\widehat{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right] \;, \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger\,\widehat{W}^{\mu\nu}\,(D_\nu\Phi) \;, \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger\,\widehat{B}^{\mu\nu}\,(D_\nu\Phi) \;, \\
\mathcal{O}_{WW} &= \Phi^\dagger\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi\,, \\
\mathcal{O}_{BB} &= \Phi^\dagger\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi\,, \\
\mathcal{O}_{\phi,2} &= \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right) \;,
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{\widetilde{W}WW} &= \mathrm{Tr}\left[\widetilde{W}^{\mu}{}_{\nu}\widehat{W}^{\nu}{}_{\rho}\widehat{W}^{\rho}{}_{\mu}\right] \;, \\
\mathcal{O}_{\widetilde{W}} &= (D_\mu\Phi)^\dagger\,\widetilde{W}^{\mu\nu}\,(D_\nu\Phi) \;, \\
\mathcal{O}_{\widetilde{B}} &= (D_\mu\Phi)^\dagger\,\widetilde{B}^{\mu\nu}\,(D_\nu\Phi) \;, \\
\mathcal{O}_{\widetilde{W}W} &= \Phi^\dagger\widetilde{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi\,, \\
\mathcal{O}_{\widetilde{B}B} &= \Phi^\dagger\widetilde{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi\,.
\end{aligned}
$$

Setup

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Setup for processes W^+W^+jj and W^+Zjj

Cuts:

$$p_{T,j} > 30\ \text{GeV}\,, \qquad |y_j| < 4.5\,, \qquad \Delta R_{j\ell} > 0.3$$
$$p_{T,\ell} > 20\ \text{GeV}\,, \qquad |y_\ell| < 2.5\,, \qquad \Delta R_{\ell\ell} > 0.3$$
$$m_{jj} > 500\ \text{GeV}\,, \qquad |\Delta y_{jj}| > 2.5\,, \qquad p_{T,\text{miss}} > 40\ \text{GeV}$$

PDF: NNPDF 3.0 NLO with $\alpha_s = 0.118$