Anomalous “Higgs” in VBFNLO

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http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

Karlsruher Institut für Technologie

VBFNLO

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arXiv:1207.4975 [hep-ph], arXiv:1107.4038 [hep-ph], arXiv:0811.4559 [hep-ph]

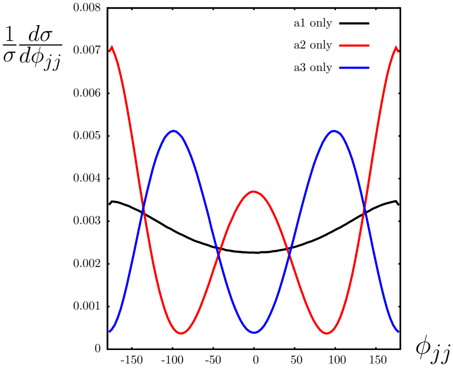
http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

Outline

HVV coupling structure

The most general *HVV* coupling is:

$$T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2)\, g^{\mu\nu} + a_2(q_1, q_2)\left(q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu}\right) + a_3(q_1, q_2)\, \epsilon^{\mu\nu\rho\sigma} q_{1\sigma} q_{2\rho}$$



HVV implementation

- VBFNLO parametrises the anomalous *HVV* couplings using effective Lagrangians. Three different Lagrangians are implemented.
- All anomalous coupling parameters are input via `anom_HVV.dat`, as described in Section 4.5 of the manual.
- The relationship between the three Lagrangian parametrisations, and the $a_{1,2,3}$ formfactors of the coupling, are all given explicitly in the "Implementation Details" section of the VBFNLO website:

http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

HVV parametrisations: I

The first parametrisation, `PARAMETR1 = .true.`, is in terms of dimension-5 operators*:

$$\begin{aligned}\mathcal{L} \;=\; & \frac{g_{5e}^{HZZ}}{2\Lambda_5} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_5} H \widetilde{Z}_{\mu\nu} Z^{\mu\nu} + \\ & \frac{g_{5e}^{HWW}}{\Lambda_5} H W^{+}_{\mu\nu} W_{-}^{\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_5} H \widetilde{W^{+}_{\mu\nu}} W_{-}^{\mu\nu} + \\ & \frac{g_{5e}^{HZ\gamma}}{\Lambda_5} H Z_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{HZ\gamma}}{\Lambda_5} H \widetilde{Z}_{\mu\nu} A^{\mu\nu} + + \\ & \frac{g_{5e}^{H\gamma\gamma}}{2\Lambda_5} H A_{\mu\nu} A^{\mu\nu} + \frac{g_{5o}^{H\gamma\gamma}}{2\Lambda_5} H \widetilde{A}_{\mu\nu} A^{\mu\nu}\end{aligned}$$

* **Figy,Zeppenfeld – hep-ph/0403297**

HVV parametrisations

The second parametrisation, `PARAMETR2 = .true.`, is in terms of dimension-6 operators*:

$$\mathcal{L}_{\text{eff}} = \frac{f_W}{\Lambda_6^2}\mathcal{O}_W + \frac{f_B}{\Lambda_6^2}\mathcal{O}_B + \frac{f_{WW}}{\Lambda_6^2}\mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda_6^2}\mathcal{O}_{BB} + \text{CP-odd part}$$

where

$$\begin{aligned}
\mathcal{O}_W &= (D_\mu\phi^\dagger)\widehat{W}^{\mu\nu}(D_\nu\phi) \\
\mathcal{O}_B &= (D_\mu\phi^\dagger)\widehat{B}^{\mu\nu}(D_\nu\phi) \\
\mathcal{O}_{WW} &= \phi^\dagger\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\phi \\
\mathcal{O}_{BB} &= \phi^\dagger\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\phi
\end{aligned}$$

* **Hagiwara,Szalapski,Zeppenfeld – hep-ph/9308347; Hagiwara,Ishihara,Szalapski,Zeppenfeld – PRD48:2182**

HVV parametrisations

The final parametrisation, `PARAMETR3 = .true.`, also uses dimension-6 operators* and is related to `PARAMETR2` as follows:

$$d = -\frac{m_W^2}{\Lambda^2}\, f_{WW} \qquad \tilde{d} = -\frac{m_W^2}{\Lambda^2}\, f_{\widetilde{W}W}$$

$$d_B = -\frac{m_W^2}{\Lambda^2}\,\frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{BB} \qquad \tilde{d}_B = -\frac{m_W^2}{\Lambda^2}\,\frac{\sin^2\theta_w}{\cos^2\theta_w}\, f_{\widetilde{B}B}$$

$$\Delta\kappa_\gamma = \kappa_\gamma - 1 = \frac{m_W^2}{2\Lambda^2}\,(f_B + f_W) \qquad \tilde{\kappa}_\gamma = \frac{m_W^2}{2\Lambda^2}\, f_{\widetilde{B}}$$

$$\Delta g_1^Z = g_1^Z - 1 = \frac{m_Z^2}{\Lambda^2}\,\frac{f_W}{2}$$

* **L3 Collaboration – hep-ex/0403037**

HVV parametrisations

Formfactors can be applied to model effective, momentum dependent HVV vertices, motivated by new physics entering with a large scale Λ at the loop level.

$$F_1 = \frac{\Lambda^2}{q_1^2 - \Lambda^2} \frac{\Lambda^2}{q_2^2 - \Lambda^2}$$
$$F_2 = -2\,\Lambda^2\, C_0\left(q_1^2, q_2^2, (q_1 + q_2)^2, \Lambda^2\right)$$

Additionally, the inputs `TREEFACZ`, `TREEFACW` and `LOOPFAC` multiply the HZZ, HWW and loop-induced $HZ\gamma$ and $H\gamma\gamma$ couplings in the SM.

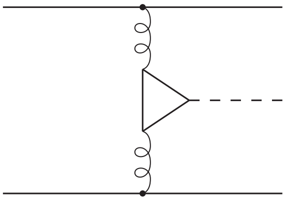
Processes with anomalous *HVV* couplings

ProcId	Process
100	$p \overset{(-)}{p} \to H\,jj$
101	$p \overset{(-)}{p} \to H\,jj \to \gamma\gamma\,jj$
102	$p \overset{(-)}{p} \to H\,jj \to \mu^+\mu^-\,jj$
103	$p \overset{(-)}{p} \to H\,jj \to \tau^+\tau^-\,jj$
104	$p \overset{(-)}{p} \to H\,jj \to b\bar{b}\,jj$
105	$p \overset{(-)}{p} \to H\,jj \to W^+W^-\,jj \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}\,jj$
106	$p \overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-\,jj$
107	$p \overset{(-)}{p} \to H\,jj \to ZZ\,jj \to \ell_1^+\ell_1^-\nu_{\ell_2}\bar{\nu}_{\ell_2}\,jj$

ProcId	Process
300	$p \overset{(-)}{p} \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$
330	$p \overset{(-)}{p} \to ZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+$
360	$p \overset{(-)}{p} \to Z\gamma \to \ell_1^-\ell_1^+\gamma$
370	$p \overset{(-)}{p} \to \gamma\gamma$
4300	$gg \to W^+W^- \to \ell_1^+\nu_{\ell_1}\ell_2^-\bar{\nu}_{\ell_2}$
4330	$gg \to ZZ \to \ell_1^-\ell_1^+\ell_2^-\ell_2^+$
4360	$gg \to Z\gamma \to \ell_1^-\ell_1^+\gamma$
4370	$gg \to \gamma\gamma$

If `ANOM_CPL` is set to `.true.` in `vbfnlo.dat`, the above processes will run with anomalous *HVV* couplings

Anomalous $Hf\bar{f}$



- PROCID 4100 simulate Hjj production via gluon fusion at LO (1-loop) level
- Anomalous $Hf\bar{f}$ couplings are parametrised by the Lagrangian

$$\mathcal{L}_{\text{Yukawa}} = \overline{q}\,(C_{\text{even}}\, y_q + i\, C_{\text{odd}}\, \gamma_5\, \tilde{y}_q)\, q\, \Phi$$

- The inputs `CP_EVEN_MOD` and `CP_ODD_MOD` can be input via the file `ggflo.dat`

JHU conversion

JHU uses the amplitude:

$$A(H \to XX) = \frac{1}{v}\epsilon_1^{*,\mu}\epsilon_2^{*,\nu}\left(a_1 g_{\mu\nu} m_X^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_\beta^2\right)$$

This converts to the VBFNLO coupling parametrisation in the following way:

$$\frac{a_1^J m_X^2}{v} = a_1^V + a_2^V q_1 \cdot q_2$$

$$\frac{a_2^J}{v} = -a_2^V$$

$$\frac{a_3^J}{v} = a_3^V$$

PRELIMINARY: check the website for confirmation!

Spin-2 effective Lagrangian

Effective Lagrangians are used to describe spin-2 singlet and triplet states:

$$\mathcal{L}_{\text{singlet}} = \frac{1}{\Lambda} T_{\mu\nu} \Big(f_1 B^{\alpha\nu} B^{\mu}_{\alpha} + f_2 W_i^{\alpha\nu} W^{i,\mu}_{\alpha} + f_3 \widetilde{B}^{\alpha\nu} B^{\mu}_{\alpha} + f_4 \widetilde{W}_i^{\alpha\nu} W^{i,\mu}_{\alpha} + 2 f_5 (D^{\mu}\Phi)^{\dagger} (D^{\nu}\Phi) \Big)$$

$$\mathcal{L}_{\text{triplet}} = \frac{1}{\Lambda} T_{\mu\nu j} \Big(f_6 (D^{\mu}\Phi)^{\dagger} \sigma^{j} (D^{\nu}\Phi) + f_7 W^{j,\mu}_{\alpha} B^{\alpha\nu} \Big)$$

A formfactor is used to ensure unitarity:

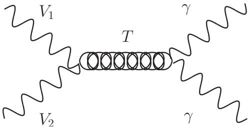
$$f(q_1^2, q_2^2, p_{\text{sp2}}^2) = \left(\frac{\Lambda_{ff}^2}{|q_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|q_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_{\text{sp2}}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}$$

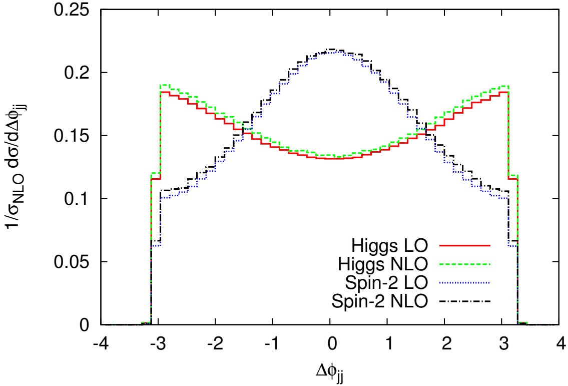
Frank,Rauch,Zeppenfeld - in preparation

Diphoton production via a spin-2 resonance

PROCID 191: $pp \to S_2\, jj \to \gamma\gamma \;\; \mathrm{jj}$

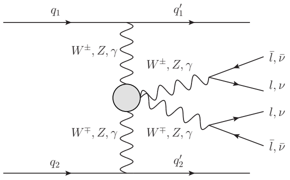
Only resonant diagrams are included



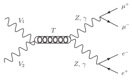


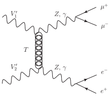
VVjj production with heavy spin-2 particles

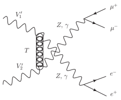
ProcId	Process
200	$p \overset{(-)}{p} \rightarrow W^+ W^- jj \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} jj$
210	$p \overset{(-)}{p} \rightarrow ZZ jj \rightarrow \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- jj$
211	$p \overset{(-)}{p} \rightarrow ZZ jj \rightarrow \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2} jj$
220	$p \overset{(-)}{p} \rightarrow W^+ Z jj \rightarrow \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^- jj$
230	$p \overset{(-)}{p} \rightarrow W^- Z jj \rightarrow \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^- jj$



ProcIDs 200-230 include both Higgs and spin-2 contributions, with full interference effects



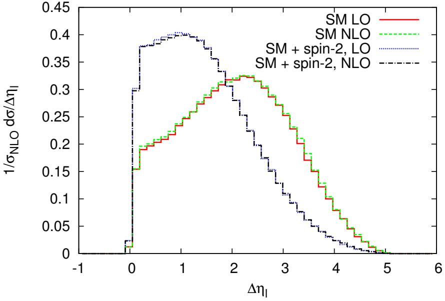




VVjj production with heavy spin-2 particles

ProcId	Process
200	$p \overset{(-)}{p} \to W^+W^- \, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^- \bar{\nu}_{\ell_2} \, jj$
210	$p \overset{(-)}{p} \to ZZ \, jj \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \, jj$
211	$p \overset{(-)}{p} \to ZZ \, jj \to \ell_1^+ \ell_1^- \nu_{\ell_2} \bar{\nu}_{\ell_2} \, jj$
220	$p \overset{(-)}{p} \to W^+Z \, jj \to \ell_1^+ \nu_{\ell_1} \ell_2^+ \ell_2^- \, jj$
230	$p \overset{(-)}{p} \to W^-Z \, jj \to \ell_1^- \bar{\nu}_{\ell_1} \ell_2^+ \ell_2^- \, jj$

ProcIDs 200-230 include both Higgs and spin-2 contributions, with full interference effects



JHU conversion

JHU describes a spin-2 singlet. The terms which are common between JHU and VBFNLO are:

$$A(X \to XX) = \frac{1}{\Lambda}\epsilon_1^{*,\mu}\epsilon_2^{*,\nu}\Big(c_1 t_{\mu\nu} + c_2 g_{\mu\nu} t_{\alpha\beta}\tilde{q}^{\alpha}\tilde{q}^{\beta} + 2c_4\left[q_{1\nu}q_2^{\alpha}t_{\mu\alpha} + q_{2\mu}q_{1\alpha}t_{\nu\alpha}\right] + c_6 t^{\alpha\beta}\tilde{q}^{\beta}\epsilon_{\mu\nu\alpha\rho}q^{\rho}\Big)$$

These are related to the VBFNLO inputs $f_1 - f_5$

$$c_1 = 2i\left(f_2 c_W^2 + f_1 s_W^2\right) q_1 \cdot q_2 + \frac{i f_5 v^2}{2}\left(g^2 + g'^2\right), \ldots$$

check the website for the full conversion!

Motivation and availability

- In order to avoid re-running the full NLO-events + shower + detector simulation + cuts, it was proposed that SM Higgs events were reweighted for anomalous couplings / spin-2
- REPOLO – Reweighting Powheg events at LO – uses the VBFNLO framework and reweights each SM event with a factor

$$\frac{|\mathcal{M}_{BSM}|^2}{|\mathcal{M}_{SM}|^2}$$

- The code is ready, but the method does have some limitations
- REPOLO will soon be “semi-public” and can be obtained

vbfnlo@particle.uni-karlsruhe.de

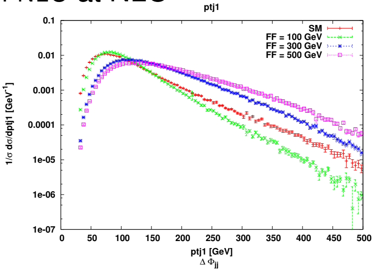
Implementation

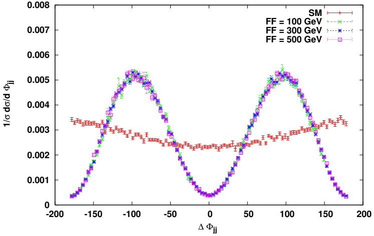
- INPUT: NLO event file
- REPOLO event reader determines:
  - Momentum and flavour configuration
  - whether the event is Born-type or real emission
  - Position of gluon
- Matrix elements $|\mathcal{M}_{SM}|^2$ and $|\mathcal{M}_{BSM}|^2$ are calculated with read-in data and explicit helicity summation
- OUTPUT: `.dat` files storing $|\mathcal{M}_{SM}|^2$ and $|\mathcal{M}_{BSM}|^2$ for each event
- OUTPUT: A PERL script then combines these `.dat` files with the original event file to produce a new event file, with every event reweighted by a factor

$$\frac{|\mathcal{M}_{BSM}|^2}{|\mathcal{M}_{SM}|^2}$$

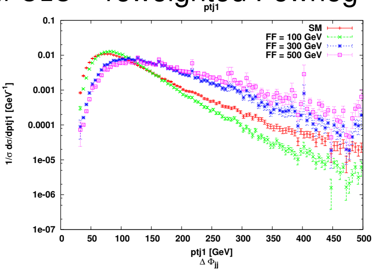
Results

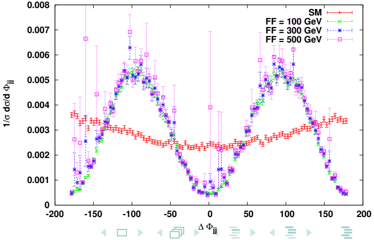
VBFNLO at NLO





REPOLO – reweighted Powheg

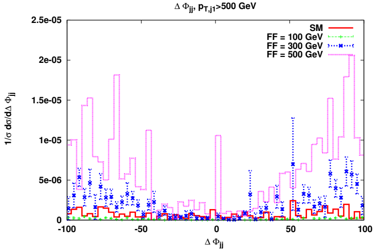


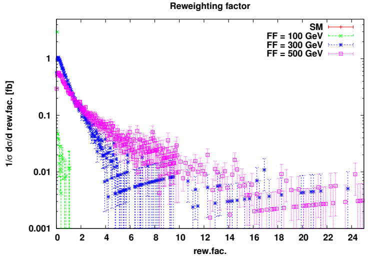


Problematic regions

- Problems occur when $|\mathcal{M}_{SM}|^2 << |\mathcal{M}_{BSM}|^2$
  - MC: $|\mathcal{M}_{SM}|^2$ small
  - reweighting: all events count
- Single events with a high reweighting factor can destroy a distribution
- A large dependence on the formfactor is observed

→ only SM-like distributions can be safely reweighted





Summary

- Anomalous Higgs couplings
  - VBF processes and gluon-induced diboson production include anomalous *HVV* couplings
  - Effective Lagrangians parametrise the anomalous *HVV* coupling. The relationship between the Lagrangians and the formfactors in the couplings is detailed on the VBFNLO webpage
  - *Hjj* production via gluon fusion includes anomalous $Hf\bar{f}$ couplings
  - A 'conversion' between VBFNLO notation and JHU notation will be on the website soon

http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

Summary

- Spin-2 model
  - VBFNLO uses an effective model to describe interactions between gauge bosons and spin-2 singlets and triplets
  - Spin-2 resonances can be investigated in the $pp \to S_2\, jj \to \gamma\gamma jj$ process
  - Spin-2 contributions can be included in addition to the SM-Higgs in $pp \to VV\, jj \to llll\, jj$
  - A 'conversion' between VBFNLO notation and JHU notation will be on the website soon

http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

Summary

- REPOLO – Reweighting Powheg events at LO
  - SM events are reweighted by a factor

$$\frac{|\mathcal{M}_{BSM}|^2}{|\mathcal{M}_{SM}|^2}$$

  - The method works in principle, but is limited to SM-like distributions
  - REPOLO will be available soon from vbfnlo@particle.uni-karlsruhe.de

http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/