VBS in VBFNLO

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HL/HE-LHC WG1 Meeting

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Vector-Boson-Fusion Physics at Next-To-Leading Order

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons at NLO QCD
- general cuts and distributions of final-state particles
- various choices for renormalization and factorization scales
- any pdf set available from LHAPDF
- event files in Les Houches Accord (LHA) or HepMC format (LO only)
- BLHA interface to Monte-Carlo event generators (for VBF processes with leptonic final states)
- NLO event output
- process optimized implementation
Process overview

- VBF-processes (VBF-approximation)
  - vector bosons (W, Z, γ)
  - vector boson scattering
    - fully leptonic incl. (ℓℓγjj)
    - all weak semi-leptonic states
    - VBF-approximation: negligible error for Δy(jj) ≃ 2
  
  VBSCAN: in preparation

- Higgs (+NLO EW, including Higgs decays)
- Higgs pair

- triboson

- diboson (+ 1 or 2 hard jets)

- Higgs + vector boson

- Higgs + two jets via gluon fusion

Full list: https://www.itp.kit.edu/vbfnlo
New Physics

- Dimension six and eight EFT operators containing bosons
- Unitarization methods (for VBS)
  - Form Factor including tool to calculate needed parameters
  - Generic T-Matrix unitarisation
    - Respecting highest involved scale: $M_{VV}$ or space-like momenta of incoming vector bosons
  - Double and single charged final states: in validation
  - Neutral final states: work in progress

- Two Higgs model
Example: Fiducial cross section for VBS

\[ pp \rightarrow W^+ (\ell^+ \nu) W^+ (\ell^+ \nu) jj \]

- for processes
  \( W^\pm W^\pm, W^\pm \gamma, W^+ W^-, ZZ, W^\pm Z, Z \gamma \)
- scan over lower cut on invariant mass \( m_{4l} \)
  \( \Rightarrow \) estimation of expected number of events

by M. Rauch
Backup
Vertex Contributions

List of Operators (only gauge and Higgs couplings)

\[
\begin{align*}
\mathcal{O}_W &= (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_{WW} &= \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \\
\mathcal{O}_{WWW} &= \text{Tr} \left[ \hat{W}^{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\rho\mu} \right] \\
\mathcal{O}_{\tilde{W}} &= (D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_{\tilde{WW}} &= \Phi^\dagger \tilde{W}_{\mu\nu} \tilde{W}^{\mu\nu} \Phi \\
\mathcal{O}_{\tilde{WWW}} &= \text{Tr} \left[ \tilde{W}^{\mu\nu} \tilde{W}^{\nu\rho} \tilde{W}^{\rho\mu} \right]
\end{align*}
\]

\[
\begin{align*}
\mathcal{O}_B &= (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_{BB} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \\
\mathcal{O}_{\phi,2} &= \partial_\mu \left( \Phi^\dagger \Phi \right) \partial^\mu \left( \Phi^\dagger \Phi \right) \\
\mathcal{O}_{\tilde{B}} &= (D_\mu \Phi)^\dagger \tilde{B}^{\mu\nu} (D_\nu \Phi) \\
\mathcal{O}_{\tilde{BB}} &= \Phi^\dagger \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} \Phi
\end{align*}
\]

Modification of corresponding triple-gauge-coupling vertices:

<table>
<thead>
<tr>
<th></th>
<th>(\mathcal{O}_{WWW})</th>
<th>(\mathcal{O}_W)</th>
<th>(\mathcal{O}_B)</th>
<th>(\mathcal{O}_{WW})</th>
<th>(\mathcal{O}_{BB})</th>
<th>(\mathcal{O}_{\phi,2})</th>
<th>(\mathcal{O}_{\tilde{WWW}})</th>
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Bosonic dimension-8 operators

\( O_{S,0} = \left( D^\mu \Phi \right)^\dagger D^\nu \Phi \times \left( D^\mu \Phi \right)^\dagger D^\nu \Phi \)

\( O_{S,1} = \left( D^\mu \Phi \right)^\dagger D^\mu \Phi \times \left( D^\nu \Phi \right)^\dagger D^\nu \Phi \)

\( O_{S,2} = \left( D^\mu \Phi \right)^\dagger D^\nu \Phi \times \left( D^\nu \Phi \right)^\dagger D^\mu \Phi \)

\( O_{M,0} = \text{Tr} \left[ \hat{W}_{\mu \nu} \hat{W}^{\mu \nu} \right] \times \left( D^\beta \Phi \right)^\dagger D^\beta \Phi \)

\( O_{M,1} = \text{Tr} \left[ \hat{W}_{\mu \nu} \hat{W}^{\nu \beta} \right] \times \left( D^\beta \Phi \right)^\dagger D^\mu \Phi \)

\( O_{M,2} = \left[ \hat{B}_{\mu \nu} \hat{B}^{\mu \nu} \right] \times \left( D^\beta \Phi \right)^\dagger D^\beta \Phi \)

\( O_{M,3} = \left[ \hat{B}_{\mu \nu} \hat{B}^{\nu \beta} \right] \times \left( D^\beta \Phi \right)^\dagger D^\mu \Phi \)

\( O_{M,4} = \left( D^\mu \Phi \right)^\dagger \hat{W}_{\beta \nu} D^\mu \Phi \times \hat{B}^{\beta \nu} \)

\( O_{M,5} = \left( D^\mu \Phi \right)^\dagger \hat{W}_{\beta \nu} D^\nu \Phi \times \hat{B}^{\beta \mu} \)

\( O_{M,7} = \left( D^\mu \Phi \right)^\dagger \hat{W}_{\beta \nu} \hat{W}^{\beta \mu} D^\nu \Phi \)

\( O_{T,0} = \text{Tr} \left[ \hat{W}_{\mu \nu} \hat{W}^{\mu \nu} \right] \times \text{Tr} \left[ \hat{W}_{\alpha \beta} \hat{W}^{\alpha \beta} \right] \)

\( O_{T,1} = \text{Tr} \left[ \hat{W}_{\alpha \nu} \hat{W}^{\mu \beta} \right] \times \text{Tr} \left[ \hat{W}_{\mu \beta} \hat{W}^{\alpha \nu} \right] \)

\( O_{T,2} = \text{Tr} \left[ \hat{W}_{\alpha \mu} \hat{W}^{\mu \beta} \right] \times \text{Tr} \left[ \hat{W}_{\beta \nu} \hat{W}^{\nu \alpha} \right] \)

\( O_{T,5} = \text{Tr} \left[ \hat{W}_{\mu \nu} \hat{W}^{\mu \nu} \right] \times \hat{B}_{\alpha \beta} \hat{B}^{\alpha \beta} \)

\( O_{T,6} = \text{Tr} \left[ \hat{W}_{\alpha \nu} \hat{W}^{\mu \beta} \right] \times \hat{B}_{\mu \beta} \hat{B}^{\alpha \nu} \)

\( O_{T,7} = \text{Tr} \left[ \hat{W}_{\alpha \mu} \hat{W}^{\mu \beta} \right] \times \hat{B}_{\beta \nu} \hat{B}^{\nu \alpha} \)

\( O_{T,8} = \hat{B}_{\mu \nu} \hat{B}_{\alpha \nu} \hat{B}_{\beta} \hat{B}^{\alpha \beta} \)

\( O_{T,9} = \hat{B}_{\alpha \mu} \hat{B}_{\mu \beta} \hat{B}_{\beta \nu} \hat{B}^{\nu \alpha} \)

\[ \rightarrow \text{each operators contains at least four bosons} \]

\[ \Rightarrow \text{leading contribution to quartic gauge coupling} \]
T-matrix (VBFNLO) for $pp \rightarrow W^+ W^+ jj$

- Non-unitarized: Events for experimental bounds originate from unphysical prediction of EFT
- T-matrix: Factor 2 – 3 lower bounds for EFT couplings
- Unitarisation methods are important
T-matrix (VBFNLO) for $pp \rightarrow W^+ W^+ jj$

<table>
<thead>
<tr>
<th>Coupling (TeV$^{-4}$)</th>
<th>CMS (13 TeV)</th>
<th>New limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{S_1} / \Lambda^4$</td>
<td>[-21.6, 21.8]</td>
<td>[-50.0, 60.3]</td>
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<tr>
<td>$f_{M_0} / \Lambda^4$</td>
<td>[-8.7, 9.1]</td>
<td>[-20.0, 14.5]</td>
</tr>
<tr>
<td>$f_{T_0} / \Lambda^4$</td>
<td>[-0.62, 0.65]</td>
<td>[-1.35, 1.60]</td>
</tr>
</tbody>
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- Non-unitarized: Events for experimental bounds originate from unphysical prediction of EFT
- T-matrix: Factor 2 – 3 lower bounds for EFT couplings
- Unitarisation methods are important