Vector-Boson-Fusion: Parton-shower and Anomalous-coupling Effects

Michael Rauch | 25 Jul 2016
VBF event topology

VBF (vector-boson fusion) topology shows distinct signature

- two tagging jets in forward region
- reduced jet activity in central region
- leptonic decay products typically between tagging jets
→ two-sided deep-inelastic scattering

First studied in context of Higgs searches \[\text{[Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; \ldots']}\]

- \(\sim 10\%\) compared to main production mode gluon fusion
- NLO QCD corrections moderate \((\mathcal{O}(\lesssim 10\%))\)
- NLO EW same size \([\text{Ciccolini et al., Figy et al.}]\)
- NNLO QCD known for subsets: no significant contributions for integrated c.s. \([\text{Harlander et al., Bolzoni et al.}]\)
  corrections up to 10\% in distributions \([\text{Cacciari et al.}]\)
- incl. NNNLO QCD: tiny effects \([\text{Dreyer, Karlberg}]\)
- advantageous scale choice: momentum transfer \(q^2\) of intermediate vector bosons
Diboson-VBF production

- Important process for LHC run-II
- Part of the NLO wish list
  - [Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings
- NLO QCD implementation of
  - all boson combinations
  - leptonic and semi-leptonic decays
  - including off-shell and non-resonant contributions
- VBF approximation

→ VBFNLO  [MR, Zeppenfeld et al.]
Introduction

VBFNLO

Vector-Boson-Fusion at Next-to-Leading Order
Introduction

VBFNLO

Physics

Vector-Boson-Fusion at Next-to-Leading Order
Introduction

VBFNLO

\textbf{Physics}

\textbf{Vector-Boson-Fusion at Next-to-Leading Order}

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
  - accurate predictions needed for LHC (both signal and background)
  - MC efficient solution for high number of final-state particles (decays of electroweak bosons included)
- general cuts and distributions of final-state particles
- various choices for renormalization and factorization scales
- any pdf set available from LHAPDF (or hard-wired CTEQ6L1, CT10, MRST2004qed, MSTW2008)
- event files in Les Houches Accord (LHA) or HepMC format (LO only)
- \textbf{BLHA interface} to Monte-Carlo event generators → \textbf{NLO} event output
Process overview

List of implemented processes

- vector-boson fusion production at NLO QCD of
  - Higgs (+NLO EW, NLO SUSY)
  - Higgs plus third hard jet
  - Higgs plus photon
  - Higgs pair
  - vector boson (W, Z, \gamma)
  - two vector bosons (W^+ W^-, W^\pm W^\pm, WZ, ZZ, W\gamma, Z\gamma)

- diboson production
  - diboson (WW, WZ, ZZ, W\gamma, Z\gamma, \gamma\gamma) (NLO QCD)
  - diboson via gluon fusion (WW, ZZ, Z\gamma, \gamma\gamma) (part of NNLO QCD contribution to diboson)
  - diboson (WW, WZ, ZZ, W\gamma) plus hard jet (NLO QCD)
  - diboson (W^\pm W^\pm, WZ, W\gamma, ZZ, Z\gamma) plus two hard jets (NLO QCD)

- triboson production (NLO QCD)
  - triboson (all combinations of W, Z, \gamma)
  - triboson (W\gamma\gamma) plus hard jet

- Higgs plus vector boson (NLO QCD) (including Higgs decays)
  - Higgs plus vector boson (WH)
  - Higgs plus vector boson plus hard jet (WH)

- Higgs plus two jets via gluon fusion (one-loop LO) (including Higgs decays)

- new physics models
  - anomalous Higgs, triple and quartic gauge couplings
  - K-matrix unitarization for selected couplings
  - Higgsless and spin-2 models
  - Two-Higgs model

- BLHA interface for VBF processes
NLO plus Parton Shower

Combine advantages of NLO calculations and parton shower

NLO calculation
- normalization correct to NLO
- additional jet at high-$p_T$
  accurately described
- theoretical uncertainty reduced

Parton shower
- Sudakov suppression at small $p_T$
- events at hadron level possible

State of the Art

Implementations for specific VBF processes
- POWHEG-BOX
  currently available VBF implementations:
  $Z$ 
  $W^\pm, Z$ 
  $W^\pm W^\pm, W^\pm W^\mp$ 
  $ZZ$

- VBF-$H$ with POWHEG method

- HJets++

[Alioli, Hamilton, Nason, Oleari, Re]

[Alioli, Hamilton, Nason, Oleari, Re]

[Schissler, Zeppenfeld]

[Jäger, Zanderighi]

[Jäger, Karlberg, Zanderighi]

[D'Errico, Richardson]

[Campanario, Figy, Plätzer, Sjödahl]
- fully automated matching of NLO to parton showers through Matchbox module
  [work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, MR, C. Reuschle]
- subtractive (MC@NLO-type, $+$) and multiplicative (POWHEG-type, $\otimes$) matching
- angular-ordered (QTilde, PS) and dipole (Dipoles) shower
- matrix elements through binary interface, no event files
VBFNLO 3 & Herwig 7 – this talk

- matrix elements from VBFNLO via BLHA2 interface
- extensions to make accessible
  - phase-space sampling
  - (electroweak) random helicity summation
  - anomalous couplings

[Binotto et al., Alioli et al.]
Validation

Compare LO results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox (inclusive cuts, with leptonic gauge boson decays into single different-flavour combination, Higgs non-decaying)

$\frac{\sigma}{\sigma_{\text{stand-alone}}}$ → good agreement at or below permill level
Validation

Compare NLO results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox
(inclusive cuts, with leptonic gauge boson decays into single different-flavour combination, Higgs non-decaying)

→ good agreement

\[ \frac{\sigma}{\sigma_{\text{stand-alone}}} \]

\[ V\gamma \text{ processes: } \pm 0.7\% \text{ deviation } \leftrightarrow \text{ beyond errors } \rightarrow \text{ under investigation} \]
Setup

Process:

\[ pp \rightarrow ((Hjj \rightarrow W^+ W^- jj \rightarrow) e^+ \nu e \mu^- \bar{\nu} \mu jj \text{ via VBF} \]

Cuts:

\[ p_{T,j} > 30 \text{ GeV} , \quad |y_j| < 4.5 , \]
anti-\( k_T \) jets with \( R = 0.4 \), \( b \)-quark veto

\[ p_{T,\ell} > 20 \text{ GeV} , \quad |y_\ell| < 2.5 , \]

\[ m_{e^+ , \mu^-} > 15 \text{ GeV} , \]

\[ m_{j1,j2} > 600 \text{ GeV} , \quad |y_{j1} - y_{j2}| > 3.6 \]

(inspired from ATLAS VBF category in \( H \rightarrow WW \), CMS similar)

PDF: MMHT2014

central scale choice: transverse momentum of the leading jet

\[ \mu_0 = p_{T,j1} \]
Distributions

Process as example: $pp \rightarrow ((Hjj \rightarrow W^+ W^- jj \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu jj)$ via VBF

Four-lepton invariant mass

- Higgs peak at 125 GeV
- $WW$ continuum production above 180 GeV
- significant cancellation between diagrams at high invariant masses
- $\Rightarrow$ ideal test for anomalous couplings
Distributions

Process as example: $pp \rightarrow (Hjj \rightarrow W^+ W^- jj \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu jj)$ via VBF

Four-lepton invariant mass

- all parton-shower results smaller than NLO cross section
- additional $K$-factor effect for LO $\oplus$ Dipoles result ($K = 1.077$)
- no relevant shape changes
  (as expected: insensitive to QCD effects)
Migration Effects

Vary transverse momentum cut of jets (default: $p_{T,j} > 30$ GeV)

- same effect when slightly raising $p_{T,j}$ cut
- additional parton splittings: if hard & wide-angle emission $\rightarrow$ separate jet
- $\rightarrow$ reduces energy and transverse momentum of emitting parton
- $\leftrightarrow p_{T,j}$ cut, VBF cut $m_{jj} > 600$ GeV
Migration Effects

Vary transverse momentum cut of jets (default: $p_{T,j} > 30 \text{ GeV}$)

- less pronounced for small $p_{T,j1}$
  - $\rightarrow$ VBF cut main source
- $\rightarrow$ migration of events across cut boundary
- $\leftrightarrow$ generation-level vs. analysis-level cuts
- $\Rightarrow$ no tuning of acceptance criteria required
- generation-level cuts nevertheless chosen weaker
central scale $\mu_0 = p_{T,j1}$
transverse momentum of leading jet

band: scale variation
$\{\mu_F, \mu_R, \mu_Q\}/\mu_0 \in [\frac{1}{2}; 2]$
$\mu_i/\mu_j \in [\frac{1}{2}; 2]$

factorization scale
$\mu_F/\mu_0 \in [\frac{1}{2}; 2]$

renormalization scale
$\mu_R/\mu_0 \in [\frac{1}{2}; 2]$

shower scale
$\mu_Q/\mu_0 \in [\frac{1}{2}; 2]$

all three scales
consistent variation of scales between hard process and parton shower

large factorization scale dependence for LO result

larger dependence for down variation of renormalization scale in angular-ordered shower:
larger $\alpha_s \rightarrow$ more splittings $\rightarrow$ bigger migration effects

small variations from shower-scale changes

modest remaining overall uncertainty
Transverse Momentum Third Jet

- large scale variation bands for
  - shower scale in $\text{LO} \oplus \text{Dipoles}$ → pure parton-shower effect
  - fact./ren. scale in “NLO” → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10 - 20\%)$
- → call for multi-jet merging
Rapidity of third jet relative to two tagging jets

\[ y_3^* = y_3 - \frac{y_1 + y_2}{2} \]

- VBF colour structure suppresses additional central jet radiation
- colour connection between tagging jet and remnant
- ↔ distinction from QCD-induced production
Rapidity of third jet relative to two tagging jets

\[ y^*_3 = y_3 - \frac{y_1 + y_2}{2} \]

- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.
- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping
- only small effects in forward region (mostly global normalization)
Rapidity of third jet – POWHEG

POWHEG-like (⊗) using resummation scheme [Plätzer]:

\[
\kappa(Q, q; \rho) = \begin{cases} 
  1 & \text{for } q < (1 - 2\rho)Q \\
  1 - \frac{(1-2\rho-q)^2}{2\rho^2} & \text{for } (1 - 2\rho)Q < q < (1 - \rho)Q \\
  \frac{(1-q)^2}{2\rho^2} & \text{for } (1 - \rho)Q < q < Q \\
  0 & \text{for } q > Q 
\end{cases}
\]

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Rapidity of third jet – POWHEG

- band: joint variation $\mu_F = \mu_R = \mu_Q \in [\frac{1}{2}, 2] \mu_0$
- similar predictions from MC@NLO-like (⊕) and POWHEG-like (⊗) matching
- also holds for other distributions
Effective Field Theory

Assumption: new physics is heavy

Classic example: $\mu$ decay $\rightarrow$ Fermi theory (t-channel $W$ integrated out)

\[
\begin{align*}
\mu & \rightarrow \nu_{\mu} \rightarrow e^- \bar{\nu}_e \\
\rightarrow & \text{ Effective Lagrangian}
\end{align*}
\]

\[
L = L_{SM} + L_{EFT} = L_{SM} + \sum_{d>4} \sum_{i} \frac{f_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}
\]

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

Important gauge cancellations between different diagram types

- longitudinal $W$ scattering through quartic gauge boson vertex

$$
\begin{array}{c}
\text{high energy limit: centre-of-mass energy } \sqrt{s} \to \infty \\
\mathcal{M}_{\text{quartic vertex}} \propto s^2 \to \text{cross section diverges } \quad \sigma \propto s^4/s = s^3 \to \infty \\
\text{add triple gauge boson vertices}
\end{array}
$$

$$
\begin{array}{c}
\mathcal{M}_{\text{quartic+triple vertices}} \propto s \to \text{still divergent} \\
\text{additional Higgs diagrams}
\end{array}
$$

$$
\begin{array}{c}
\text{remove divergence exactly } \quad \sigma \propto 1/s \to 0 \\
\text{Anomalous gauge couplings spoil cancellation } \to \text{stringent tests}
\end{array}
$$
Unitarization

Anomalous gauge couplings spoil cancellation
\(\leftrightarrow\) effects can become large \(\rightarrow\) unitarity violation

Several solutions:

- consider only unitarity-conserving phase-space regions
  throws away information \(\rightarrow\) reduced sensitivity
- (dipole) form factor multiplying amplitudes

\[
\mathcal{F}(s) = \frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n}
\]

\(\Lambda_{FF}^2, n: \) free parameters

- \(K\)-matrix unitarization \hspace{1em} [Alboteanu, Kilian, Reuter, Sekulla]
  based on partial-wave analysis \hspace{1em} [Jacob, Wick]
  project amplitude back onto Argand circle

![Graphs and diagrams related to unitarity and anomalous couplings]
Cross Section Results

Example Process: \( pp \rightarrow W^+ W^+ jj \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj \) at NLO QCD accuracy

- kink form factor (simplified projection for comparison):
  \[
  F_{\text{kink}}(E) = \begin{cases} 
  1 & \text{for } E \leq \Lambda_{\text{FF,kink}}, \\
  \left( \frac{\Lambda_{\text{FF,kink}}}{E} \right)^4 & \text{for } E > \Lambda_{\text{FF,kink}}.
  \end{cases}
  \]

- huge effects for un-unitarized result \( \leftrightarrow \) unphysical
- \( K \)-matrix method maximising contribution while staying in physical region
- \( \rightarrow \) study parton-shower and hadronization impact
Combination with Parton Shower

Can also combine K-matrix in setup with parton shower

Example: VBF-$W^+ W^+$ ($pp \rightarrow e^+ \nu_e \mu^+ \nu_\mu jj$)

anom. coupl.: $f_{S,1} = 100 \text{ TeV}^{-4}$

No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix) )
Combination with Parton Shower

Can also combine K-matrix in setup with parton shower

Example: VBF-$W^+W^+$ \((pp \rightarrow e^+\nu_e\mu^+\nu_\mu jj)\)

anom. coupl.: \(f_{S,1} = 100 \text{ TeV}^{-4}\)

\[ m_{4\ell} \text{ – Comparison} \]

\[ p_{j,3}^T \text{ – Comparison} \]

No significant shape changes in \(m_{4\ell}\) when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix) )

\(\leftrightarrow p_{j,3}^T\) mostly sensitive to parton-shower effects
Conclusions

Parton-shower and scale variation effects in \( W^+ W^- jj \) production via vector-boson-fusion

- **important** process for the LHC
  - Higgs properties – unitarity in WW scattering
  - testing anomalous (triple and) quartic gauge couplings

- **study performed** with **Herwig 7 & VBFNLO 3**

- **compatible** behavior of both parton showers and matching schemes

- **small** parton-shower effects for distributions of variables already present at LO
  - mostly reduction of inclusive cross section due to additional jet radiation

- **presence of central rapidity gap stabilised**

  \[
  \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i e \bar{\psi} [\gamma_\mu, \gamma_5, \not{c}] \psi y_i + h.c.
  \]

  \[
  y_i : y_0, y_2, \not{c} + h.c.
  \]

  \[
  \not{p}_T - V(0)
  \]

- \( \rightarrow \) **multi-jet merging** to further reduce uncertainties

- \( \rightarrow \) **study hadronization impact**
Conclusions

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  $\rightarrow$ **study hadronization** impact
BLHA Interface

Defined standardized interface between Monte Carlo tools and one-loop programs


- tree-level evaluation of matrix elements well under control
- modular structure of NLO calculations
- algorithms for treatment of infrared singularities (Catani-Seymour, FKS, . . . )
- → incorporate one-loop matrix element information into MC tools

Distribution of tasks:

- MC tool:
  - cuts, histograms, parameters
  - Monte Carlo integration
  - phasespace (→ VBFNLO)
  - IR subtraction
  - Born, colour- and spin-correlated Born (only BLHA1)

- One-loop provider (OLP):
  - one-loop matrix elements $2\Re(\mathcal{M}_\text{LO}^\dagger \mathcal{M}_\text{virt})$ (coefficients of $\epsilon^{-2}$, $\epsilon^{-1}$, $\epsilon^0$; $|\mathcal{M}_\text{LO}|^2$)
  - Born, colour- and spin-correlated Born (only BLHA2)

Setup stage via “contract” file
(needed for tools which generate code on the fly)
Run-time stage via binary interface (function calls) → fast
Validation

Compare LO+j results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox

(inclusive cuts, with leptonic gauge boson decays into single different-flavour combination, Higgs non-decaying)

→ good agreement
Setup

Generation-level cuts:

\[ p_T, j > 20 \text{ GeV} , \quad |y_j| < 5.0 , \]
\[ \text{anti-}k_T \text{ jets with } R = 0.4 , \quad b\text{-quark veto} \]
\[ p_T, \ell > 15 \text{ GeV} , \quad |y_\ell| < 3.0 , \]
\[ m_{e^+, \mu^-} > 15 \text{ GeV} , \]
\[ m_{j_1, j_2} > 400 \text{ GeV} , \quad |y_{j_1} - y_{j_2}| > 3.0 \]

Analysis-level cuts:

\[ p_T, j > 30 \text{ GeV} , \quad |y_j| < 4.5 , \]
\[ \text{anti-}k_T \text{ jets with } R = 0.4 , \quad b\text{-quark veto} \]
\[ p_T, \ell > 20 \text{ GeV} , \quad |y_\ell| < 2.5 , \]
\[ m_{e^+, \mu^-} > 15 \text{ GeV} , \]
\[ m_{j_1, j_2} > 600 \text{ GeV} , \quad |y_{j_1} - y_{j_2}| > 3.6 \]
Missing Transverse Momentum

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Transverse Momentum of Leading Lepton

\[
\frac{d\sigma}{dp_{T,l1}} \ [fb/GeV]
\]

Herwig 7
VBFNLO 3

\[
\frac{\sigma_i}{\sigma_{NLO}}
\]

\[
\mu_F
\]

\[
\mu_R
\]

\[
\mu_Q
\]

\[
\mu_{tot}
\]

\[
p_{T,l1} \ [GeV]
\]

NLO
LO ⊕ Dipoles
NLO ⊕ Dipoles
NLO ⊕ PS
$\Delta R = \sqrt{\Delta y^2 + \Delta \phi^2}$

Jacobian peak at $\Delta R_{j1\ell1} = \pi$
NNLO QCD Correction to VBF-H

- NNLO effects well approximated by NLO plus parton-shower results

[Cacciari, Dreyer, Karlberg, Salam, Zanderighi]