Vector-Boson-Scattering – VBFNLO update

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Outline

- VBFNLO overview
- Recent enhancements
  - Semileptonic decays
  - Form factor tool
- Backgrounds: QCD-\(WZjj\)
- Parton-shower matching: VBF-H
Introduction

VBFNLO

- 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)
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
  - vector boson (W, Z, \(\gamma\))
  - two vector bosons (\(W^+W^-\), \(W^\pm W^{\pm}\), WZ, ZZ; \(W\gamma\) will be in final VBFNLO 2.7.0)

- 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 (WZ, W\(\gamma\)) plus hard jet (NLO QCD)

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

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

- new physics models
  - anomalous Higgs couplings
  - anomalous triple and quartic gauge couplings
  - Higgsless and spin-2 models

Intermediate state Higgs boson in all processes included where applicable
Implementation Details

- Helicity amplitude method
- Same building blocks for different Feynman graphs
  ⇒ Compute only once per phase-space point and reuse ("leptonic tensors")
  → Significantly faster than generated code (up to factor 10)

\[ e^+ + \nu_e + \mu^- + \mu^+ + Z/\gamma^* + \gamma \]

\[ g + q + q' \]

\[ g + \bar{q} + \bar{q}' \]

[Hagiwara, Zeppenfeld]
Implementation Details

- Catani-Seymour dipole subtraction scheme

\[ \sigma_{\text{NLO}} = \int_{m+1} \left[ d\sigma^R|_{\varepsilon=0} - d\sigma^A|_{\varepsilon=0} \right] + \int_m \left[ d\sigma^V + \int_1 d\sigma^A \right]_{\varepsilon=0} + \int_m d\sigma^C \]

- real emission
- virtual contributions
- finite collinear term

- Photon isolation à la Frixione
  Processes with real photons in final state can have configurations with photon collinear to final-state quark → QED divergence
  Simple (e.g. R) separation cut between photon and jet not infrared safe
  → Frixione photon isolation

\[ \sum_i E_{T_i} \Theta(\delta - R_{i\gamma}) \leq p_{T\gamma} \frac{1 - \cos \delta}{1 - \cos \delta_0} \]  
  (for all \( \delta \leq \delta_0 = 0.7 \))

⇒ Efficiently suppresses fragmentation contribution
Diboson-VBF production

- Part of the NLO wishlist
  - [Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings

Implementation:
- modular structure
  - → reuse building blocks
- leptonic decays included
- only t- and u-channel diagrams
  - (s-channel implemented separately as triboson process)
- no interference effects from identical leptons

\[\text{[Denner, Hosekova, Kallweit (W}^+\text{W}^+\text{)]}\]
Semileptonic Decays

- Vector bosons have significant branching fractions into $q\bar{q}$ final states
  \[ BR(W \rightarrow q\bar{q}) \approx BR(Z \rightarrow q\bar{q}) \approx 70\% \]
- ⇒ Extend decay modes and let one vector boson decay hadronically
  ⇒ semi-leptonic final states

- Vector-boson-fusion processes only contain t-channel exchange
- s-channel contribution can be viewed as triboson production with one vector boson decaying hadronically
- interference between s- and t-channel small
  ⇒ can be treated as separate process
- ↔ s-channel contribution small in phenomenologically interesting phase-space regions ($M_{jj,\text{cut}} \gg M_V$)
Semileptonic Decays

- Semileptonic decays implemented in the following channels:
  - \( pp \rightarrow VVjj \) via VBF with \( VV \in W^+ W^-, W^\pm W^\pm, W^\pm Z, ZZ \)
  - \( pp \rightarrow Hjj \rightarrow VVjj \) via VBF with \( VV \in W^+ W^-, ZZ \)
  - \( pp \rightarrow VV \) with \( VV \in W^+ W^-, W^\pm Z, ZZ \)
  - \( pp \rightarrow W^+ W^- Z \) (other combinations will follow soon)

- Factor \( K = 1 + \frac{\alpha_s}{\pi} \) for \( V \rightarrow q\bar{q} \) decay can be added as NLO approximation for decay (assuming resonant \( V \) production dominates)

- Non-resonant contributions included

- Virtual photon decays \( \gamma^* \rightarrow q\bar{q} \)
  - can form single jet in real emission part
  - quarks massless \( \Rightarrow \) divergence \( \Leftrightarrow \) pion mass as regulator in reality
  - \( \Rightarrow \) technical cut \( \rightarrow \) cross section depends on value
  - \( \Rightarrow \) estimate size from \( e^+ e^- \rightarrow \) hadrons without modelling resonances explicitly

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Tagging jet definition

- two widely separated jets characteristic VBF signature
- leptonic decays: two hardest jets
- semileptonic decays: jet can come from vector boson decay ⇒ not a good choice
- alternatives:
  - two jets with largest distance in rapidity
    → works for signal, but bad background rejection
  - separate phase space explicitly:
    - tagging jets: $|\eta_{\text{tag}}| > \eta_c$, $\eta_1 \times \eta_2 < 0$
    - vector boson decay products: $|\eta_{\text{decay}}| < \eta_c$
    - require high-$p_T$ jet in central region

$$pp \to H(\to W^+ W^-)jj$$

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Anomalous quartic gauge couplings

Vector-boson scattering ideal process to test anomalous quartic gauge couplings

[New in VBFNLO 2.7.0beta: Feigl, Schlimpert]

Dimension-8 operators in Lagrangian

($\phi$ Higgs doublet, $W^\mu_\nu/B^\mu_\nu$: SU(2)/U(1) field strength tensors):

$$\mathcal{L}_{M,2} \propto [B^\mu_\nu B^\mu_\nu] \times \left[ (D^\beta \phi)^\dagger D_\beta \phi \right]$$

$$\mathcal{L}_{T,1} \propto [W^\alpha_\nu W^\mu_\beta] \times [W^\mu_\beta W^\alpha_\nu]$$

\ldots

(at least) four gauge fields in each term $\rightarrow$ modify quartic gauge couplings

triple gauge couplings contribute as well
Form factor tool

Contribution of higher-dimensional operators can violate unitarity above certain energy scale \( \rightarrow \) unphysical

- Determine energy scale of unitarity violation \( \rightarrow \) Partial-wave analysis
  - Consider amplitudes for on-shell \( VV \rightarrow VV \) scattering \( (V \in W, Z, \gamma) \)
  - Decompose into series of partial waves with coefficients \( a_i, i = 0, 1, 2, \ldots \)
  - \( \rightarrow \) Condition for unitarity conservation: \( |\text{Re}(a_i)| < \frac{1}{2} \)
  - Strongest bound typically from \( i = 0 \) \( \rightarrow \) check only this contribution

\( \Rightarrow \) maximal energy scale \( \Lambda_{\text{max}} \)

- Ensure unitarity at higher energies by applying form factor
  - Unitarity preserved by new-physics contributions entering at or before \( \Lambda_{\text{max}} \)
    \( \rightarrow \) acts as cut-off
  - effective implementation in low-energy theory \( \Rightarrow \) form factor
  - explicit form model-dependent \( \rightarrow \) choice arbitrary
  - VBFNLO: dipole form factor

\[ \mathcal{F}(s) = \frac{1}{(1 + \frac{s}{\Lambda_{\text{FF}}^2})^n} \]
\( \Lambda_{\text{FF}}, n: \) free parameters

- Determine maximal \( \Lambda_{\text{FF}} \) from given anomalous couplings, \( n \) and maximum energy considered

\( \rightarrow \) implemented in form factor tool available from VBFNLO web site

Example output

[...] Reading in anomalous couplings parameter:
  SQRT_S = 14000.
  FFEXP = 2.0000
  FS0 = 0.10000E-09
  FS1 = 0.10000E-09
[...] Checking tree-level unitarity violation with on-shell W+W- -> W+W- scattering using the largest helicity combination of the zeroth partial wave...
[...] Checking tree-level unitarity violation with on-shell VV->VV scattering including all Q=0 channels involving W and Z bosons using the largest helicity combination of the zeroth partial wave...
[...] Results for each channel, taking only the helicity combination with the largest contribution to the zeroth partial wave into account:

  FFscale_WWWW = 688. GeV  ( without FF: |Re(pwave_0)| > 0.5 at  0.8 TeV )
[...] No tree-level unitarity violation in W+W- -> AA scattering found.
[...] Results for each channel, taking contributions from all helicity combinations to the zeroth partial wave into account by diagonalizing the T-matrix:

  FFscale_WWWW_diag = 688. GeV  ( without FF: |Re(pwave_0)| > 0.5 at  0.8 TeV )
  FFscale_VVVV_Q_0 = 622. GeV  ( without FF: |Re(pwave_0)| > 0.5 at  0.7 TeV )
[...]
Anomalous quartic gauge couplings

Anomalous couplings enhance predominantly high-energy region

\[ \Delta \sigma \sim O(1 - 4\%) \] for total cross section,
\[ \Delta \sigma \sim O(20 - 100\%) \] in high-energy region, \( m_{WW}^T > 800 \text{ GeV} \)

Visible changes in distributions, different for individual couplings

\( \rightarrow \) distinguish between different couplings
QCD-Diboson production

$W^+ W^+ jj$ and $W^+ W^- jj$ known at NLO QCD for some time

[Melia, Melnikov, Röntsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]

$W^+ W^- jj$ & $W^+ W^+ jj$
(latter after changing quark flavors appropriately)

+ diagrams where quark line without attached vector bosons is replaced by gluons
QCD-induced $WZjj$ production ($\mathcal{O}(\alpha^4\alpha_s^2)$)

- Born: 90 subprocesses

- virtual corrections: up to rank-5 hexagons

- real emission: 146 subprocesses
Speed comparison

**W⁺ Zjj @ LO**

Runtime for 0.1% accuracy:
- VBFNLO: 8 min
- Sherpa: 5 h
- MadGraph 5: 1 month (based on extrapolation: 0.7% in 14 hours)

**W⁺ W⁺ jj @ NLO**

VBFNLO:
- 30 min for 1% accuracy

POWHEG-BOX:
- 200 jobs, 3 days each
- Best result:
  - 8% accuracy
- Median:
  - 60% accuracy
- Worst result:
  - Off by factor 10^6 (with error as large)
- Combined result:
  - 1.1% (weighted mean)

Origin of better performance
- Get rid of numerical instabilities
- Combine and reuse similar contributions
- Good phase-space generator
**Scale variation**

\[ pp \rightarrow e^+\nu e^+\mu^-jj, \sqrt{S} = 14 \text{ TeV} \]

- cuts
  \[ p_T,j > 20 \text{ GeV}, \quad |\eta_j| < 4.5 \]
  \[ p_{T,\ell} > 20 \text{ GeV}, \quad |\eta_{\ell}| < 2.5 \]
  \[ m_{\ell^+\ell^-} > 15 \text{ GeV}, \quad p_T > 30 \text{ GeV} \]
  \[ R_{jj} > 0.4, \quad R_{\ell\ell} > 0.4 \]
  \[ R_{j\ell} > 0.4 \]

- PDF
  MSTW 2008 with \( n_F = 4 \)

- scale
  \[ \mu = \mu_F = \mu_R \]
  \[ = \frac{1}{2} \left( \sum_{\text{jet}} p_{T,\text{jet}} + E_{T,W} + E_{T,Z} \right) \]
  with \( E_{T,V} = \sqrt{p_{T,V}^2 + m_V^2} \)

→ scale dependence strongly reduced
Distributions

→ Differential K factor varying in distributions
Matching with Parton Shower

VBFNLO interfaced to Herwig++

requires some process-dependent modifications
⇒ currently only VBF-Higgs production, further processes will follow

→ Matching NLO calculations with parton shower

NLO calculation

- normalization correct to NLO
- additional jet at high-\(p_T\)
  accurately described
- theoretical uncertainty reduced
- low-\(p_T\) jet emission badly modelled
- parton level description

LO + parton shower

- LO normalization only
- further high-\(p_T\) jets badly described
- Sudakov suppression at small \(p_T\)
- events at hadron level possible

⇒ Herwig++ package Matchbox

Parton shower based on Catani-Seymour dipoles
Matching methods: MC@NLO and POWHEG

NLO validation plot

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Shower effects at LO

- Transverse momentum $p_{Tj3}$
- Rapidity $y_{j3}$

- Additional radiation by shower created mainly between jets and beam axis (color connections)
- Dipole shower “interpolates” between NLO behavior in central region and shower behavior at small angles
NLO matching

Rapidity $y_3$

$y_3^* = y_3 - \frac{1}{2} \left( y_1 + y_2 \right)$
Conclusions

- New features in VBFNLO
  - Semi-leptonic decays for $VVjj$, $VV$, $WWZ$
  - Form factor tool
determine energy bound for unitarity violation in anomalous gauge couplings
calculate necessary form factor

- QCD-$WZjj$ at NLO QCD
  fast implementation in VBFNLO

- Matching with parton shower

VBFNLO is a flexible parton-level Monte Carlo for processes with electro-weak bosons

Code available at
http://www.itp.kit.edu/vbfnlo

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