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

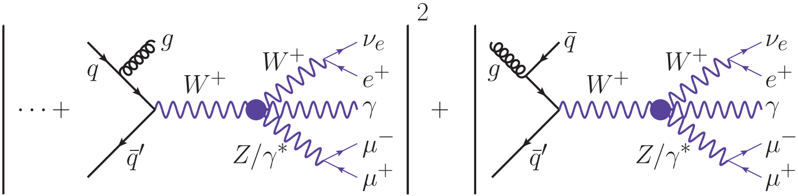
- vector-boson fusion production at NLO QCD of
  - Higgs (+NLO EW, NLO SUSY)
  - Higgs plus third hard jet
  - Higgs plus photon

  } (including Higgs decays)
  - vector boson (W, Z, γ)
  - 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, γ) (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 [Hagiwara, Zeppenfeld]
- Same building blocks for different Feynman graphs
  $\Rightarrow$ Compute only once per phase-space point and reuse ("leptonic tensors")
  $\rightarrow$ Significantly faster than generated code (up to factor 10)



Implementation Details

- Catani-Seymour dipole subtraction scheme

$$\sigma_{\text{NLO}} = = \underbrace{\int_{m+1} [\mathrm{d}\sigma^R|_{\epsilon=0} - \mathrm{d}\sigma^A|_{\epsilon=0}]}_{\text{real emission}} + \underbrace{\int_m [\mathrm{d}\sigma^V + \int_1 \mathrm{d}\sigma^A]_{\epsilon=0}}_{\text{virtual contributions}} + \underbrace{\int_m \mathrm{d}\sigma^C}_{\text{finite collinear term}}$$

- Photon isolation à la Frixione
  Processes with real photons in final state can have configurations with photon collinear to final-state quark $\rightarrow$ QED divergence

  Simple (e.g. R) separation cut between photon and jet not infrared safe
  $\rightarrow$ Frixione photon isolation

$$\sum_i E_{T_i} \Theta(\delta - R_{i\gamma}) \leq p_{T_\gamma} \frac{1 - \cos\delta}{1 - \cos\delta_0} \qquad (\text{for all} \quad \delta \leq \delta_0 = 0.7)$$

  $\Rightarrow$ Efficiently suppresses fragmentation contribution

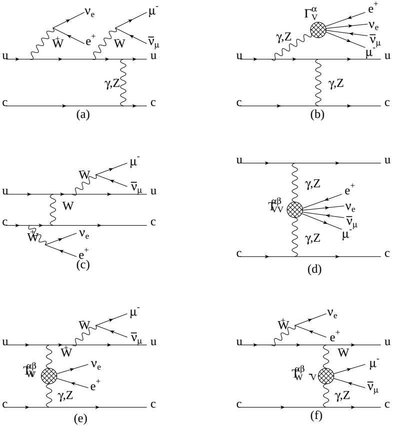
Diboson-VBF production

[Bozzi, Jäger, Oleari, Zeppenfeld; hep-ph/0603177, hep-ph/0604200, hep-ph/0701105]
[Denner, Hosekova, Kallweit (W^+W^+)]

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

Implementation:

- modular structure
  $\rightarrow$ 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

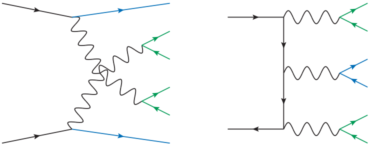


Semileptonic Decays

[New in VBFNLO 2.7.0beta: Feigl]

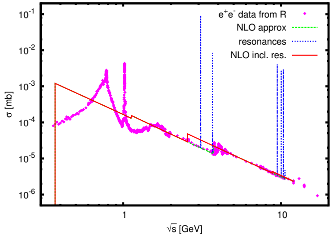
- Vector bosons have significant branching fractions into $q\bar{q}$ final states
  $BR(W \to q\bar{q}) \simeq BR(Z \to q\bar{q}) \simeq 70\%$
- $\Rightarrow$ Extend decay modes and let one vector boson decay hadronically
- $\Rightarrow$ semi-leptonic final states

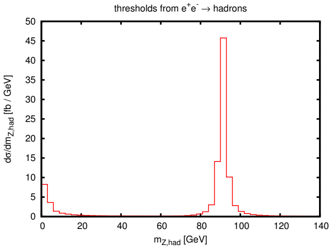
- Vector-boson-fusion processes only contain t-channel exchange
- s-channel contribution can be viewed as
  triboson production with one vector boson decaying hadronically
- interference between s- and t-channel small
  $\Rightarrow$ can be treated as separate process
- $\leftrightarrow$ s-channel contribution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



Semileptonic Decays

- Semileptonic decays implemented in the following channels:
  - $pp \to VVjj$ via VBF with $VV \in W^+W^-,\ W^\pm W^\pm,\ W^\pm Z,\ ZZ$
  - $pp \to Hjj \to VVjj$ via VBF with $VV \in W^+W^-, ZZ$
  - $pp \to VV$ with $VV \in W^+W^-,\ W^\pm Z,\ ZZ$
  - $pp \to W^+W^-Z$ (other combinations will follow soon)
- Factor $K = 1 + \frac{\alpha_s}{\pi}$ for $V \to q\bar{q}$ decay can be added as NLO approximation for decay (assuming resonant V production dominates)
- Non-resonant contributions included
- Virtual photon decays $\gamma^* \to q\bar{q}$
  - can form single jet in real emission part
  - quarks massless $\Rightarrow$ divergence $\leftrightarrow$ pion mass as regulator in reality
  - $\Rightarrow$ technical cut $\to$ cross section depends on value
  - $\Rightarrow$ estimate size from $e^+e^- \to$ hadrons without modelling resonances explicitly

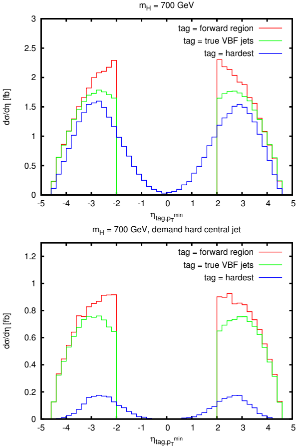




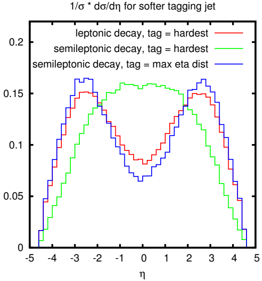
Tagging jet definition

- two widely separated jets characteristic VBF signature
- leptonic decays: two hardest jets
- semileptonic decays: jet can come from vector boson decay $\Rightarrow$ not a good choice
- alternatives:
  - two jets with largest distance in rapidity
    $\rightarrow$ 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

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



$pp \rightarrow W^+W^-jj$ via VBF, inclusive cuts



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
(Φ Higgs doublet, $W^{\mu\nu}/B^{\mu\nu}$: SU(2)/U(1) field strength tensors):

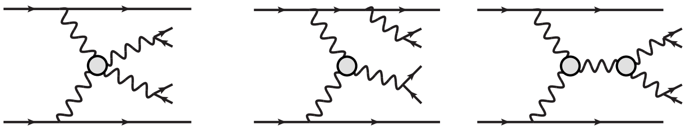
$$\mathcal{L}_{M,2} \propto [B^{\mu\nu} B_{\mu\nu}] \times \left[\left(D^{\beta}\Phi \right)^{\dagger} D_{\beta}\Phi \right]$$

$$\mathcal{L}_{T,1} \propto \left[W^{\alpha\nu} W_{\mu\beta} \right] \times \left[W^{\mu\beta} W_{\alpha\nu} \right]$$

$$\ldots$$

(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: $|\mathrm{Re}(a_i)| < \frac{1}{2}$
  - Strongest bound typically from $i = 0$ $\rightarrow$ check only this contribution

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

$$\mathcal{F}(s) = \frac{1}{\left(1 + \frac{s}{\Lambda_{\mathrm{FF}}^2}\right)^n} \qquad \Lambda_{\mathrm{FF}}^2,\ n\text{: free parameters}$$

- Determine maximal Λ_{FF} from given anomalous couplings, n and maximum energy considered

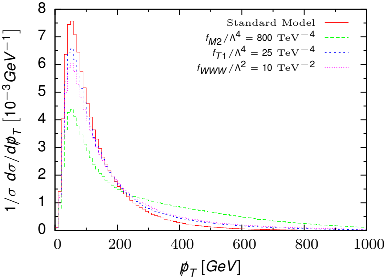
$\rightarrow$ implemented in form factor tool available from VBFNLO web site
`http://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=download:formfactor`

Example output

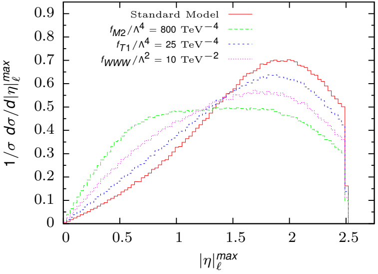
```
[...]
 Reading in anomalous couplings parameter:
   SQRT_S                = 14000.
   FFEXP                 = 2.0000
   FS0                   = 0.10000E-09
   FS1                   = 0.10000E-09
[...]
 Checking tree-level unitarity violation with on-shell W+W- -> W+W- scattering
 using the largest 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

Normalized $\not{p}_t$ distribution



Normalized $|\eta|_\ell^{max}$ distribution



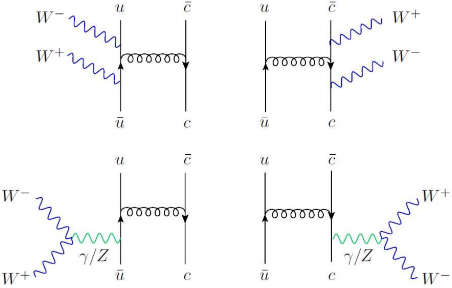
- Anomalous couplings enhance predominantly high-energy region
- $\Delta\sigma \sim \mathcal{O}(1-4\%)$ for total cross section,
  $\Delta\sigma \sim \mathcal{O}(20-100\%)$ in high-energy region, $m_{WW}^T > 800$ GeV
- Visible changes in distributions, different for individual couplings
- $\rightarrow$ distinguish between different couplings

QCD-Diboson production

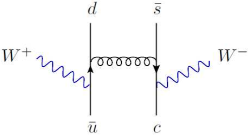
$W^+ W^+jj$ and $W^+ W^-jj$ known at NLO QCD for some time

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

W^+W^-jj



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



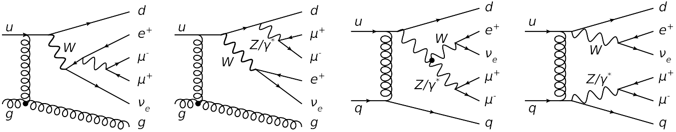
+ diagrams where quark line without attached vector bosons is replaced by gluons

WZjj production

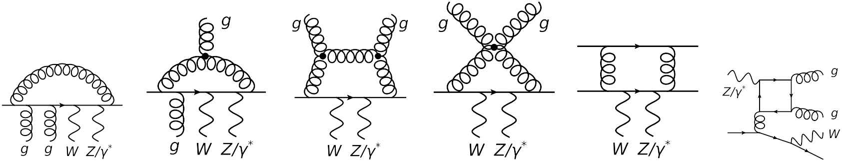
[Campanario, Kerner, Le, Zeppenfeld; will be in final VBFNLO 2.7.0]

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

Karlsruhe Institute of Technology

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^+Zjj @ NLO

runtime for 1% accuracy:

- VBFNLO: 2-3 h

Origin of better performance

- get rid of numerical instabilities
- combine and reuse similar contributions
- good phase-space generator

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)

Scale variation

$pp \to e^+ \nu_e \mu^+ \mu^- jj$, $\sqrt{S} = 14$ TeV

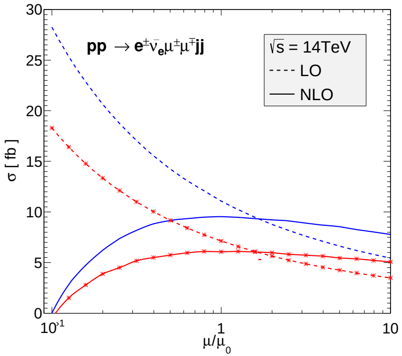
- cuts

$$
\begin{aligned}
p_{T,j} &> 20 \text{ GeV} & |\eta_j| &< 4.5 \\
p_{T,\ell} &> 20 \text{ GeV} & |\eta_\ell| &< 2.5 \\
m_{\ell^+\ell^-} &> 15 \text{ GeV} & \not{p}_T &> 30 \text{ GeV} \\
R_{jj} &> 0.4 & R_{\ell\ell} &> 0.4 \\
R_{j\ell} &> 0.4
\end{aligned}
$$

- PDF
  MSTW 2008 with $n_F = 4$
- scale

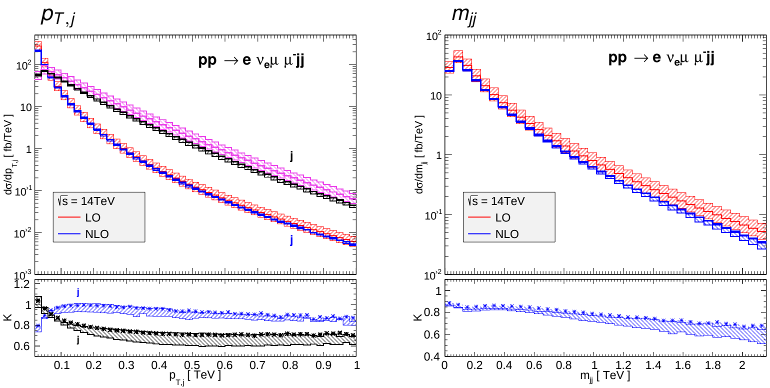
$$
\begin{aligned}
\mu &= \mu_F = \mu_R \\
&= \frac{1}{2}\left(\sum_{\text{jet}} p_{T,\text{jet}} + E_{T,W} + E_{T,Z}\right)
\end{aligned}
$$

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

[New in VBFNLO 2.7.0 beta + upcoming Herwig++ release: Arnold et al.]

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

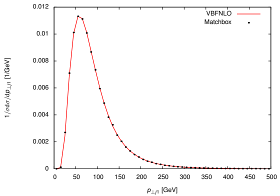
LO + parton shower

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

⇒ Herwig++ package Matchbox [Gieseke, Plätzer]

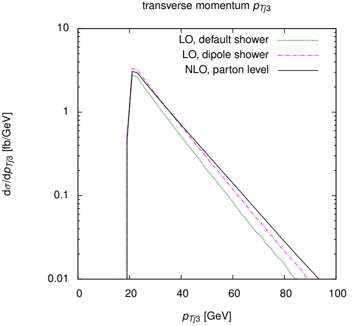
Parton shower based on Catani-Seymour dipoles

Matching methods: MC@NLO and POWHEG

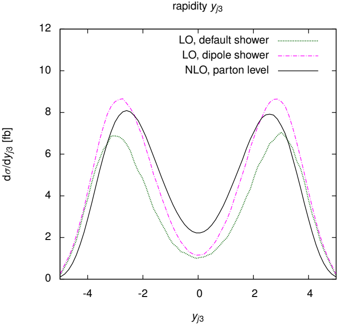


NLO validation plot

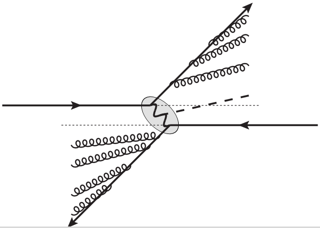
Shower effects at LO



Transverse momentum of third hardest jet

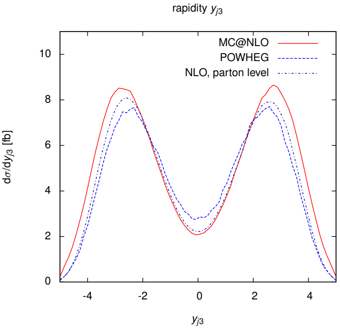


Rapidity of third hardest jet

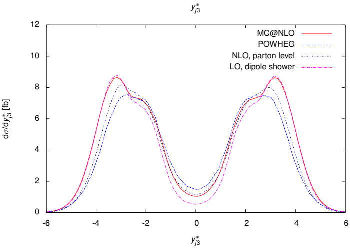


- additional radiation by shower created mainly between jets and beam axis (color connections)
- dipole shower "interpolates" between NLO behavior in central region and shower behavior at small angles

NLO matching



Rapidity of third hardest jet



$$y^*_{j3} = y_{j3} - \frac{1}{2}\left(y_{j1} + y_{j2}\right)$$

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`

VBFNLO is collaborative effort:

K. Arnold, J. Bellm, G. Bozzi, M. Brieg, F. Campanario, C. Englert, B. Feigl, J. Frank, T. Figy, F. Geyer, N. Greiner, C. Hackstein, V. Hankele, B. Jäger, M. Kerner, G. Klämke, M. Kubocz, C. Oleari, S. Palmer, S. Plätzer, S. Prestel, MR, H. Rzehak, F. Schissler, O. Schlimpert, M. Spannowsky, M. Worek, D. Zeppenfeld

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