VBFNLO: A parton level Monte Carlo for processes with electroweak bosons

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Outline

VBFNLO

- In order to take advantage of the data from the LHC, we need to be able to produce accurate cross section predictions for both signal and background processes.
- Monte Carlo methods allow us simulate final states with several jets and/or identified particles and impose the kinematic cuts that are needed for the LHC.
- VBFNLO is a fully flexible parton level Monte Carlo program that can simulate vector boson fusion, and double and triple vector boson production for the LHC at NLO QCD:

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

arXiv:0811.4559[hep-ph]

Implemented processes

Various signal and background processes are implemented at NLO QCD in VBFNLO:

- Vector boson fusion processes:
  - Higgs production with two or three jets: 1-loop electroweak corrections included
  - Higgs production in association with a photon and two jets: New process
  - Vector boson production with two jets: Additional process included
  - Double vector boson production with two jets

Implemented processes

Various signal and background processes are implemented at NLO QCD in VBFNLO:

- Double and triple vector boson production: More processes included
- Double vector boson production in association with a hadronic jet: New processes

Additionally, Higgs production via gluon fusion at LO is coded: Squark loop effects included

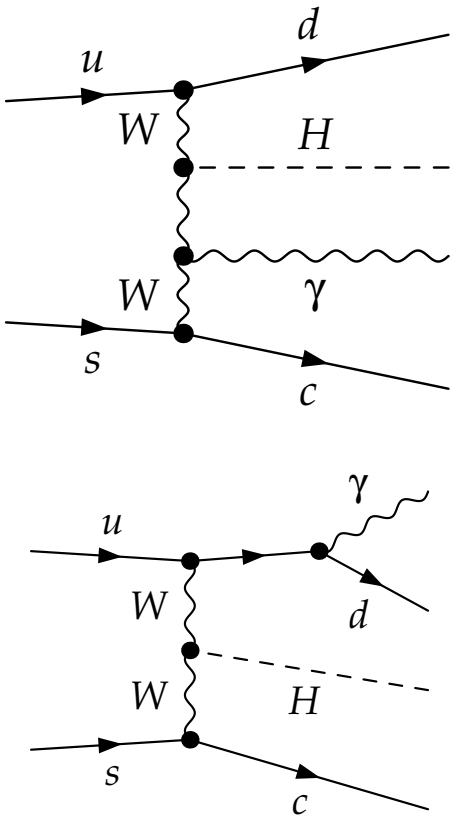
Electroweak corrections to Higgs production via VBF

The electroweak corrections to Higgs production via VBF are of the same order as the QCD corrections – approximately 5%.

The new release of VBFNLO has the full electroweak corrections in the SM and the dominant corrections in the MSSM. Various approximations are possible:

- Only third generation quark (and squark) contributions are considered
- Only fermion (and sfermion) contributions are considered
- In the MSSM, only sfermion and SM-type corrections are included
- In the MSSM, the chargino and neutralino boxes and pentagons are neglected

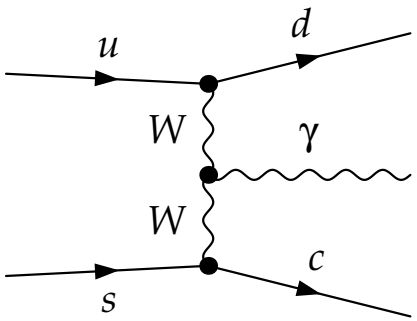
Higgs production in association with a photon

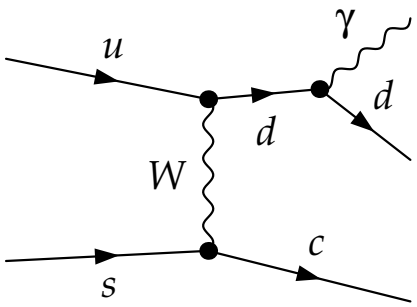


- By requiring a hard photon in association with the Higgs produced via VBF, the signal to background ratio of the $Hb\bar{b}$ mode can be improved.
- The photon isolation criterion of Frixione is used.
- The QCD corrections to the integrated cross sections are small, while the shape of kinematic distributions can be distorted by up to 20%.

Photon production via VBF

- The process $H \to \gamma jj$ provides us with access to the triple gauge boson vertex.
- The photon isolation criterion of Frixione is used.
- NLO QCD corrections enhance the integrated cross section by $\sim 10\%$, and change the shape of several distributions.
- Anomalous gauge boson couplings affect the distributions in a manner distinct from the NLO QCD corrections, providing sensitivity to BSM effects.



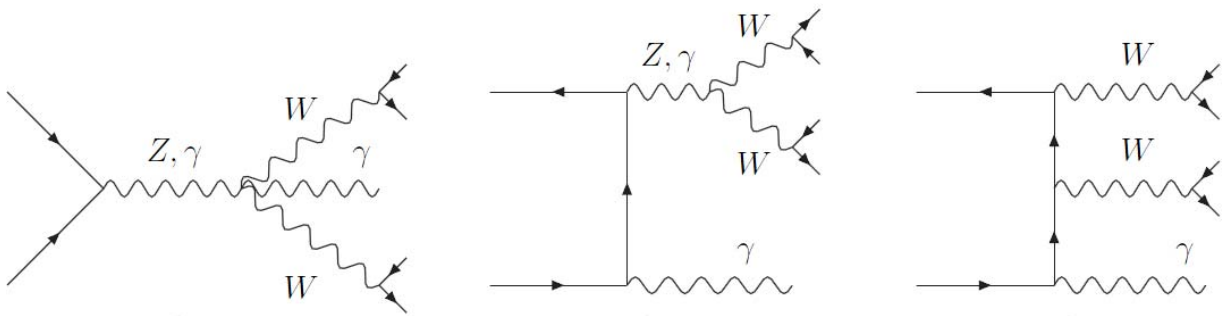


Triboson production

- New physics signatures at the LHC tend to include missing transverse momentum, jets, and high p_T leptons.
- Events with multiple gauge bosons in the final state are an irreducible background to many of these processes.
- They also provide sensitivity to anomalous triple and quartic gauge boson couplings.
- The new processes implemented have large NLO QCD corrections and demonstrate a strong dependence on the observable and phase space.
- The LO scale variations lead to an underestimate of these corrections.

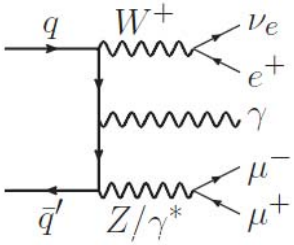
Triboson production: $WW\gamma$ and $ZZ\gamma$

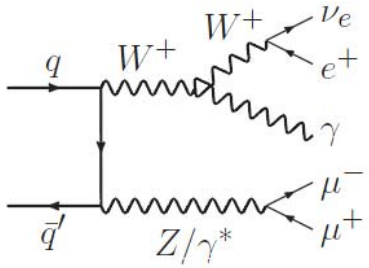
- $WW\gamma$ and $ZZ\gamma$ production provide the opportunity to study triple gauge couplings
- Additionally, $WW\gamma$ production is sensitive to the quartic couplings $WWZ\gamma$ and $WW\gamma\gamma$

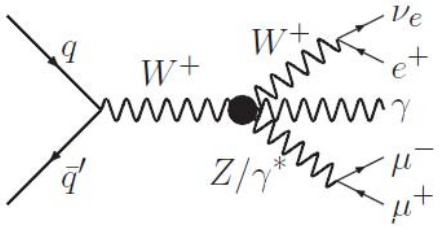


Triboson production: $WZ\gamma$

- The production of $WZ\gamma$ allows us to access the quartic gauge boson couplings $WWZ\gamma$ and $WW\gamma\gamma$.

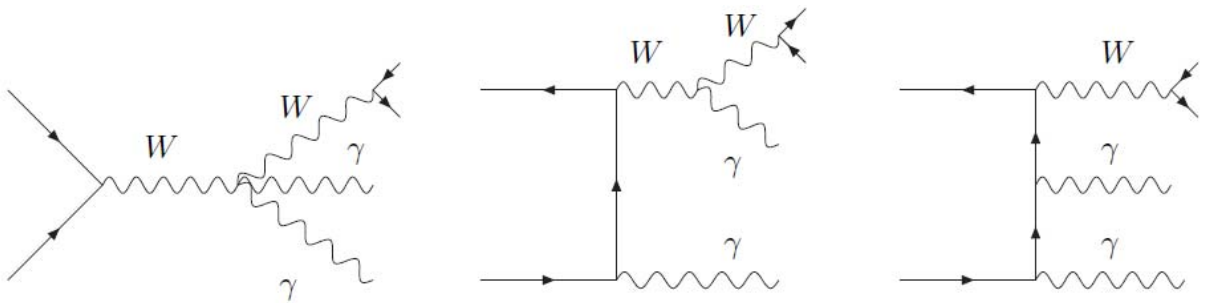






Triboson production: W$\gamma\gamma$, Z$\gamma\gamma$, $\gamma\gamma\gamma$

- W$\gamma\gamma$, Z$\gamma\gamma$ and $\gamma\gamma\gamma$ provide important backgrounds to BSM processes.
  - W$\gamma\gamma$ and Z$\gamma\gamma$ can mimic neutralino decay in GMSB.
  - $\gamma\gamma\gamma$ is a background for techi-pion production with a photon.
- W$\gamma\gamma$ gives us access to the $WW\gamma$ and $WW\gamma\gamma$ couplings.



Double vector boson production in association with a hadronic jet

- WZj and $W\gamma j$ production have significant NLO QCD corrections (up to $\sim 40\%$), which are strongly dependent on phase space.
- They are, in some regions of phase space, sensitive to the anomalous triboson couplings $WW\gamma$ and WWZ.
- This sensitivity can be obscured by NLO QCD corrections and scale uncertainties.

Higgs and weak boson decays

- Full spin-correlations and all off-shell effects are included.
- VBFNLO can simulate various Higgs decays:
  - $H \to \gamma\gamma$
  - $H \to \mu^+\mu^-$
  - $H \to \tau^+\tau^-$
  - $H \to b\bar{b}$
  - $H \to W^+W^- \to l_1^+ \nu_{l_1} l_2^- \overline{\nu_{l_2}}$
  - $H \to ZZ \to l_1^+ l_1^- l_2^+ l_2^-$
  - $H \to ZZ \to l_1^+ l_1^- \nu_{l_2} \overline{\nu_{l_2}}$
- Decay widths and branching ratios are taken from:
  - Internal calculation
  - SLHA file
  - FeynHiggs calculation

vbfnlo.dat: I

The main physics and output parameters are input via the file `vbfnlo.dat`:

- Process type
- Monte Carlo parameters
- Corrections included in the calculation
- Beam parameters
- Renormalisation and factorisation scales:
  - User-defined constant scales
  - Momentum transfer of exchanged W/Z bosons (VBF)
  - $\min(p_T(j_i))$ (VBF)
  - invariant mass of VV/VVV system (di/triboson)
  - $\sqrt{p_T(j_1) \times p_T(j_2)}$ (gluon fusion)

vbfnlo.dat: II

The main physics and output parameters are input via the file vbfnlo.dat:

- Higgs mass and type
- Quark masses
- Electroweak parameters (M_W, G_F, ..)
- Strong coupling constant α_s
- PDF choice: The user can choose:
  - Link to LHAPDF
  - cteq6ll and CT10
  - mrst2004qed

vbfnlo.dat: III

The main physics and output parameters are input via the file vbfnlo.dat:

- VBFNLO can generate parton level event files in the LHA format.
- A basic set of histograms is generated in various formats
  - Data files
  - ROOT files
  - TOPDRAWER files
  - GNUPLOT files

cuts.dat

A basic set of cuts is provided by VBFNLO:

- Jet specific cuts (R_{jj},..)
- Lepton specific cuts ($p_{T_l,min}$,..)
- Photon specific cuts ($p_{T_\gamma,min}$,..)
- VBF specific cuts ($\eta_{jj,min}$, tagging jets found in opposite hemispheres,..)

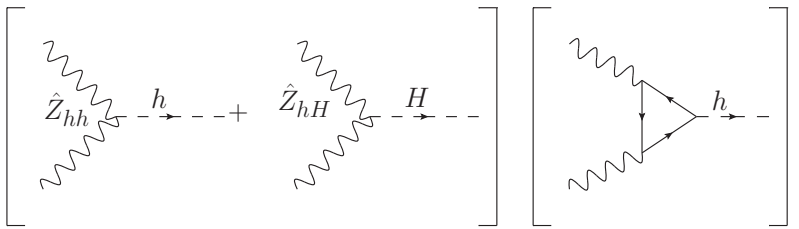
Working in the MSSM: I

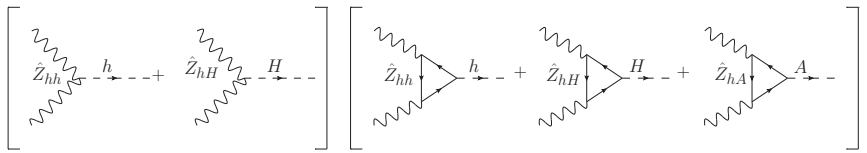
- Production of any of the three neutral Higgs bosons can be studied
- SUSY parameters can be input in various ways
  - `VBFNLO` can be linked with `FeynHiggs` in order to evaluate the Higgs sector of the MSSM
    - User-input
    - Various benchmark scenarios (M_h^{max}, gluophobic, no-mixing, small α_{eff}, CPX)
    - Snowmass points and slopes (SPS)
  - A SLHA file can be used to define all SUSY parameters

Working in the MSSM: II

The effects of mixing between the neutral Higgs bosons can be extremely important.

- These effects can be included in several ways:
  - An effective Higgs mixing angle can be used
  - Propagator-type corrections can be included at LO
  - Propagator-type corrections can be included at LO and loop level
  - Propagator-type corrections can be included as an additional 'counterterm'





Kaluza-Klein models

Diboson production via VBF can be studied in a Warped-Higgsless model, as can the triboson processes *WWW*, *WWZ*, *WZZ*. These triboson processes can also be simulated in a Three-Site Higgsless model.
The user can input:

- All Kaluza-Klein parameters by hand

Or VBFNLO can calculate the parameters based on:

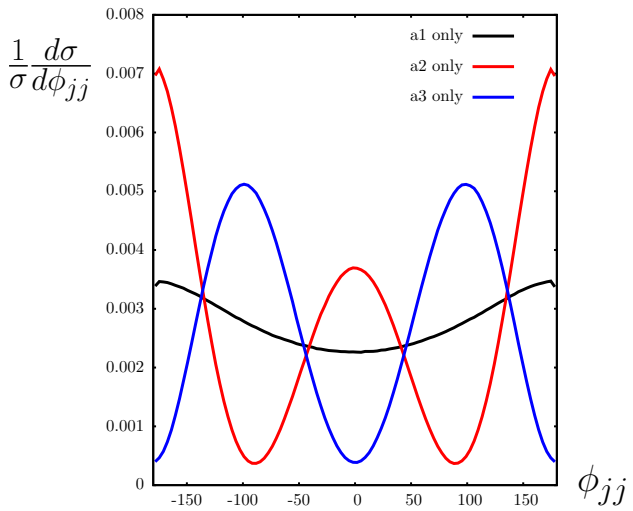
- The location of the UV brane
- The maximum number of Kaluza-Klein $W_k^{\pm}$, Z_k and Z_k' states to be included

Anomalous Higgs couplings

Anomalous Higgs couplings *HVV* can be studied in the production and decay of VBF type processes.

Three different parametrisations can be used, with inputs of the type:

- Scale of new physics
- Coefficients of operators in the effective Lagrangian



The structure of the Higgs-Vector-Vector coupling can in principle be studied via the azimuthal angle distribution.

Anomalous vector boson couplings

Anomalous triple and quartic vector boson couplings can be studied in the triboson processes that do not include a photon, and in WZj and $W\gamma j$ production.

The couplings are defined via

- Scale of new physics
- Coefficients of operators in the effective Lagrangian

Future plans

Future additions to VBFNLO are planned, including:

- Parton shower matching with HERWIG
- Diboson production with anomalous couplings
- Higgs + 3 jets via gluon fusion
- Implementation of massive leptons in the final states
- ...

Summary

- VBFNLO is a fully flexible, parton level Monte Carlo program for the simulation of vector boson processes at NLO QCD.
- New processes that can be simulated include:
  - Higgs production via VBF in association with a photon
  - Photon production via VBF
  - $W\gamma j$ and WZj production
  - Triboson production: $WW\gamma$, $ZZ\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$
- Various BSM effects are included:
  - Simulation in the MSSM with real or complex parameters
  - Anomalous couplings of the Higgs and gauge bosons
  - Kaluza-Klein models
- Electroweak corrections to Higgs production via VBF in the SM and MSSM are implemented
- The new version should be released in the next two months!

References

- Electroweak corrections to VBF: T. Figy, S. Palmer, G. Weiglein – **arXiv:1012.4789[hep-ph]**
- Higgs production with a photon: K. Arnold, T. Figy, B. Jäger, D. Zeppenfeld – **arXiv:1006.4237[hep-ph]**
- Photon production via VBF: B. Jäger – **arXiv:1004.0825[hep-ph]**
- $WW\gamma$ and $ZZ\gamma$ production: G. Bozzi, F. Campanario, V. Hankele, D. Zeppenfeld – **arXiv:0911.0438[hep-ph]**
- $WZ\gamma$ production: G. Bozzi, F. Campanario, M. Rauch, H. Rzehak, D. Zeppenfeld – **arXiv:1011.2206[hep-ph]**
- $W\gamma\gamma$, $Z\gamma\gamma$ and $\gamma\gamma\gamma$: G. Bozzi, F. Campanario, M. Rauch, D. Zeppenfeld, **in preparation**
- WZj and $W\gamma j$ production: F. Campanario, C. Englert, M. Spannowsky, D. Zeppenfeld – **arXiv:0908.1638[hep-ph]**; F. Campanario, C. Englert, S. Kallweit, M. Spannowsky, D. Zeppenfeld – **arXiv:1006.0390[hep-ph]**; F. Campanario, C. Englert, M. Spannowsky – **arXiv:1006.3090[hep-ph]**; F. Campanario, C. Englert, M. Spannowsky – **arXiv:1010.1291[hep-ph]**