VBFNLO 0.9

NLO parton level Monte Carlo for VBF processes

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April 25, 2007

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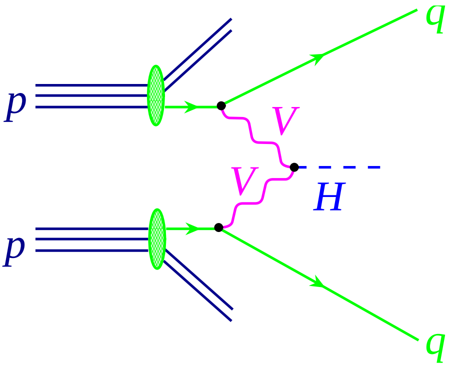
Outline

What is VBFNLO

- Parton level Monte Carlo for various **V**ector **B**oson **F**usion processes at **NLO** QCD.
- Arbitrary cuts can be implemented.
- Get cross sections at LO and NLO QCD.
- Get arbitrary differential distributions at LO and NLO $\rightarrow$ differential K-Factors.
- Weighted or unweighted event files (LHA format).

Higgs production in **V**ector **B**oson **F**usion



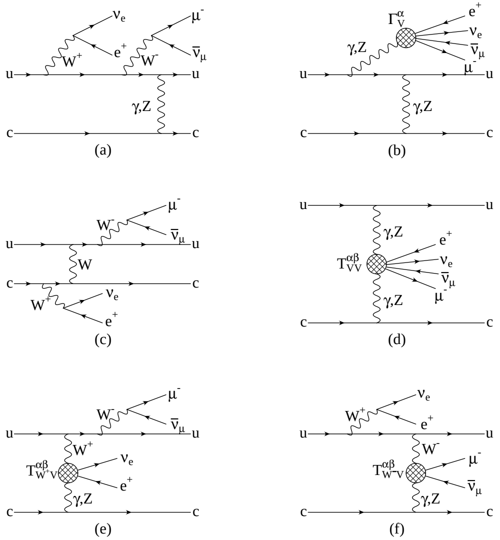
Higgs production in **V**ector **B**oson **F**usion

- $\sigma(qq \to qqH) \sim 20\% \cdot \sigma(gg \to H)$ at the LHC
- Clean experimental signature
  - Two highly energetic outgoing jets
  - Large rapidity interval between jets, with little hadronic activity in it.

  $\longrightarrow$ Ability to exploit double jet tagging and central jet veto.
- allows precise measurement of Higgs couplings (HWW, HZZ, H$f\bar{f}$)
- expected statistical accuracies on measured $\sigma \times BR$ of order 10%

$\longrightarrow$ Very promising channel at the LHC. But LO calculation may not be enough to match the experimental uncertainties!

VV production in Vector Boson Fusion

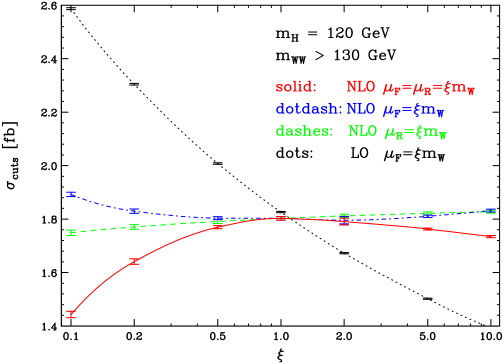


VV production in Vector Boson Fusion

- Background to Higgs production via VBF
  - $\sigma(qq \rightarrow qqW^+W^-)$ between 3.5% and 15% of the Higgs signal for 115 GeV $\leq M_H \leq$ 160 GeV [Kauer,Plehn,Rainwater,Zeppenfeld(2001)]
  - similar features as H production $\Rightarrow$ irreducible background
- New Physics
  - possible signal: enhancement of $qq \rightarrow qqVV$ over SM predictions at large $\sqrt{s}$
  - subprocess $V_L V_L \rightarrow V_L V_L$ intimately related to EWSB

$\longrightarrow$ Need accurate predictions for EW VVjj production as well!

Scalevariation for WW production in VBF



- NLO corrections moderate and under theoretical control.
- Scale choice arbitrary, but cross section dependence on it only disappears for all orders of pertubation theory.
- Choose scales such that K $\approx$ 1: NLO calculation needed.

Outline

Processes in VBFNLO

NLO QCD:

$pp \to Hjj$	[T. Figy, C. Oleari, D.Zeppenfeld, PRD68, 073005 (2003)]
$pp \to Hjj,\ H \to \tau^+\tau^-$	in NWA
$H \to \gamma\gamma,\ H \to \bar{b}b$	in NWA
$pp \to Hjj,\ H \to WW \to \ell^+\ell^-\nu\bar{\nu}$	
$pp \to WWjj \to \ell^+\ell^-\nu\bar{\nu}jj$	[B. Jäger, C. Oleari, D.Zeppenfeld, JHEP 0607, 015 (2006)]
$pp \to ZZjj \to \ell^+\ell^-\ell^+\ell^-jj$	[B. Jäger, C. Oleari, D.Zeppenfeld, PRD73, 113006 (2006)]
$pp \to ZZjj \to \ell^+\ell^-\nu\bar{\nu}jj$	
$pp \to Hjj$ (with anom. couplings)	[T. Figy, V. Hankele, G. Klämke, D.Zeppenfeld, PRD74, 095001 (2006)]
$pp \to Wjj \to \ell\nu jj$	[C. Oleari, D.Zeppenfeld, PRD69, 093004 (2004)]
$pp \to Zjj \to \ell^+\ell^-jj$	[C. Oleari, D.Zeppenfeld, PRD69, 093004 (2004)]
$pp \to Zjj \to \nu\bar{\nu}$	

LO:
all processes plus additional jet

future processes in VBFNLO

NLO QCD:

$pp \to WZjj \to \ell^+\ell^-\ell\nu jj$ [G.Bozzi, B. Jäger, C. Oleari, D.Zeppenfeld, PRD 75, 073004 (2007)]

$pp \to V'jj \to \ldots$ [C. Englert diploma thesis (Kaluza Klein excitations from extra dimensions)]

$\ldots \to W \to jj$ [M. Werner diploma thesis (hadronic W decays)]

LO:

$pp \to Hjj$ [via gluon fusion (work in progress)]

Performance

LO eventfiles on an AMD Athlon 64 2.2 GHz

process	events	time	unweighting
$pp \to Hjj$	13427	11s	5.1 %
$pp \to H(\to WW)jj$	10929	34s	1.0 %
$pp \to Hjjj$	16564	2m 9s	0.79 %
$pp \to Wjj$	9976	8m 52s	0.06 %
$pp \to WWjj$	9208	1h 16m	0.1 %

NLO cross sections and distributions on an Intel Centrino 1.8 GHz

process	error	time
$pp \to H(\to WW)jj$	0.7 %	2m 6s
$pp \to Wjj$	0.7 %	9m 4s
$pp \to WWjj$	1.1 %	42m

LHC run. All weak bosons decayed leptonically.

Outline

1. Introduction
2. Features
   - Processes
   - Tools
   - I/O
3. Tutorial
   - Differential K-factor

Tools for the calculation

- Amplitudes are calculated using helicity amplitudes (HELAS [Murayama et. al., KEK-91-11] , MADGRAPH [Maltoni et. al., JHEP 0302:027,2003]).
- MC integration + stratified sampling is done with a modified version of VEGAS. [Lepage, CLNS-80/447]
- Optimized phasespace for up to 7 particles in the final state.
- PDF via LHAPDF or built-in CTEQ6 tables.
- NO mandatory external libraries.
- Parallelized through the specification of random number seeds. Runs on CondorClusters.
- Easy to add new histograms or cuts.

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Input/Output

Input files:

`vbfnlo.dat`	Modify the main options: process ID, beam energy, beam particles, scale choice, pdfset, output format etc.
`cuts.dat`	Specify the values of the implemented cuts.
`anom-WW.dat`	Set anomalous couplings for the bosons.
`anom-HVV.dat`	Set anomalous Higgs couplings.
`random.dat`	Set the seeds of the random number generator.

Output:

- Histograms: ROOT[1], Gnuplot, Topdrawer, Paw[2]
- LHA eventfiles as ASCII files.

[1] if ROOT is installed
[2] if CERNLIB is installed

Outline

Tutorial

Goal:

Calculate the differential K-Factor for an arbitrary observable for the process $pp \longrightarrow Hjj, H \longrightarrow WW \longrightarrow e^+\mu^-\bar{\nu}\nu$ using typical VBF cuts.

Getting started

1. Download the code: http://www-itp.physik.uni-karlsruhe.de/vbfnlo
2. Extract it

```
$ tar xzvf vbfnlo.tar.gz
```

3. Compile it i.e. adjust the Makefile
   - Choose your fortran compiler (if it is not called g77)
     potential problems with g77 version ≥ 4
   - Enter the library paths, you want to link to (CERNLIB or LHAPDF)
   - Enable the desired libraries, e.g.

```
WITH_LHAPDF = 1
WITH_CERNLIB = 0
WITH_ROOT = 1
```

Configure VBFNLO

4. Adjust `vbfnlo.dat`
   LaTeX files are provided in `./doc/` to explain the options.

```
PROCESS = 0112          !  Identifier for process
NLO_ITERATIONS = 4      !  number of iterations (LO)
NLO_POINTS = 22         !  number of points for LO (= 2^N)
NLO_SWITCH = true       !  switch:  nlo/lo calculation
ID_MUF = 12             !  ID for factorization scale
```

```
ROOT = true                !  create root-file
REPLACE = true             !  replace output files?
ROOTFILE = histograms      !  name of root-file ( + '.root')
```

Configure VBFNLO

5. Adjust cuts.dat

```
RJJ_MIN = 0.8d0    !  min jet-jet R separation
Y_MAX = 5.0d0      !  max pseudorapidity for partons
NJET_MIN = 2       !  min no.  of defined jets
```

6. Set VBF cuts e.g.

```
ETAJJ_MIN = 4d0     !  min rapidity gap size
YSIGN = true        !  taggingjets:  y1 · y2 < 0
LRAPIDGAP = true    !  leptons fall inside rapidity gap
```

New histograms

7. Add a new histogram in `.src/histograms.F`
   First book it:

subroutine InitHistograms

```
+ call CreateHist(ID, title, #bins, min, max)
```

Then calculate your observable from the 4vector arrays
`real*8 jets(0:7,max_jets), leptons(0:7,max_v)`

subroutine HistogramEvent(...)

```
+ call FillHist(ID, value, dw, NLO)
```

→ get the histogram for LO and NLO

Finally...

8. Recompile
9. Run the code

```
$ ./vbfnlo
```