VBFNLO

NLO Parton Level Monte Carlo for VBF

Małgorzata Worek
Karlsruhe University (ITP)
CERN 4 June 2007

http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/

Outline

- *What is VBFNLO*
- *Why we need VBFNLO - signal versus background*
- *Features of VBF processes*
- *Features of VBFNLO parton level MC program*
- *How to use VBFNLO*
- *Results* $qq \to qqH$, $qq \to qqW^+W^-$
- *Summary & Outlook*

Manuel Bähr, Giuseppe Bozzi, Christoph Englert, Terrance Figy, Co Georg, Jan Germer, Nicolas Greiner, Vera Hankele, Barbara Jäger, Gunnar Klämke, Partha Konar, Michael Kubocz, Carlo Oleari, Matthias Werner, MW, Dieter Zeppenfeld

VBFNLO

- Parton level Monte Carlo for various VBF processes at NLO QCD
- Arbitrary cuts can be implemented
- Various scale choices and PDF sets
- Cross sections at LO and NLO QCD
- Arbitrary differential distributions at LO and NLO
- Anomalous HVV couplings both in the production and decay of the Higgs boson
- Anomalous triple gauge couplings in WWjj
- K-Factors and differential K-Factors
- Weighted/unweighted events and LHA format files

NLO QCD:

$pp \to Hjj$
$pp \to Hjj, \quad H \to \tau\tau$
$pp \to Hjj, \quad H \to \gamma\gamma$
$pp \to Hjj, \quad H \to b\bar{b}$
$pp \to Hjj, \quad H \to WW \to l^+l^-\nu\bar{\nu}$
$pp \to WWjj \to l^+l^-\nu\bar{\nu}jj$
$pp \to ZZjj \to l^+l^-l^+l^-jj$
$pp \to ZZjj \to l^+l^-\nu\bar{\nu}jj$
$pp \to Wjj \to l\nu jj$
$pp \to Zjj \to l^+l^-jj$
$pp \to Zjj \to \nu\bar{\nu}jj$

LO:

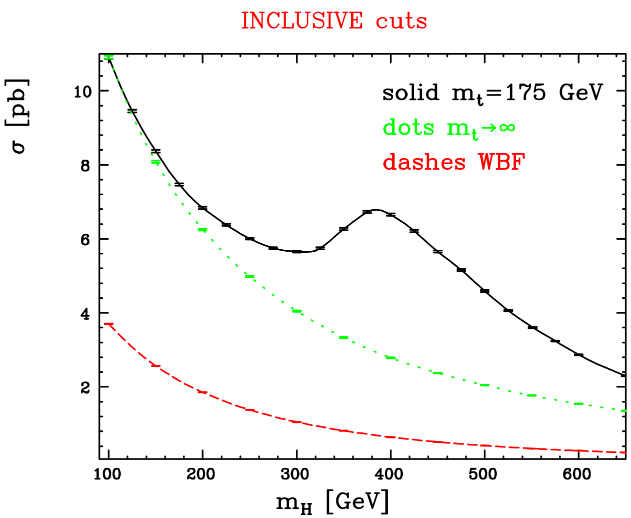
All processes plus additional jet

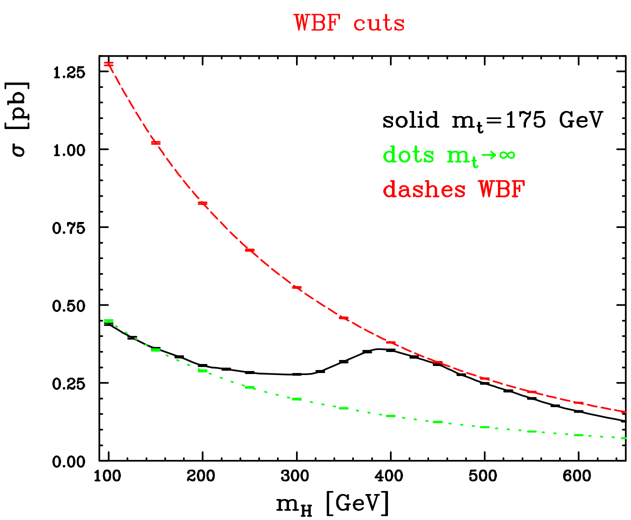
Higgs Production in VBF

- $\sigma(qq \to qqH) \sim 20\%\, \sigma(gg \to H)$ at the LHC
- Clean experimental signature
  - Energetic jets in forward and backward directions $p_T > 20$ GeV
  - Large rapidity separation and large invariant mass of two tagging jets
  - Higgs decay products between tagging jets
  - Little gluon radiation in the central rapidity region due to colourless W/Z exchange
- Double jet tagging and central jet veto to suppress QCD backgrounds
- Allows precise measurement of Higgs couplings $\Rightarrow$ $HWW, HZZ, Hf\bar{f}$
- At the LHC with statistical accuracies on $\sigma \times BR$ of order 10%

D. Zeppenfeld, R. Kinnunen, A. Nikitenko, E. Richter-Was, Phys. Rev. D62, 013009 (2000)

Higgs Production in VBF





- *H + 2j cross section at the LHC as a function of* m_H
- *Inclusive cuts*
  - $p_{T_j} > 20$ GeV
  - $|\eta_j| < 5$
  - $\Delta R_{jj} > 0.6$
- *VBF cuts*
  - $|\eta_{j_1} - \eta_{j_2}| > 4.2$
  - $\eta_{j_1} \cdot \eta_{j_2} < 0$
  - $m_{j_1 j_2} > 600$ GeV

V. Del Duca, W. Kilgore, C. Oleari, C. Schmidt, D. Zeppenfeld, Phys. Rev. Lett. 87, 122001 (2001)

WW production in VBF

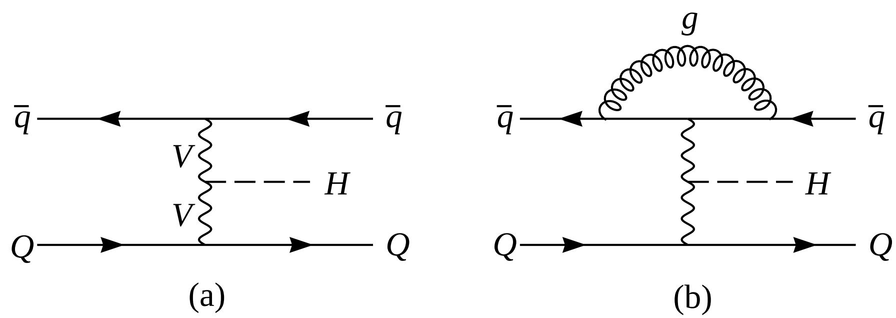
- Background to Higgs production via VBF
  - $\sigma(qq \to qqW^+W^-)$ between 15% and 3.5% of the Higgs signal for $115\,GeV \leq M_H \leq 160\,GeV$

N. Kauer, T. Plehn, D.L. Rainwater, D. Zeppenfeld, Phys. Lett. B503, 113 (2001)

- Similar features as H production $\Rrightarrow$ Irreducible background
  - t-channel colour-singlet exchange VBF process
  - Kinematic distributions of the two tagging jets
  - Suppression of gluon radiation in the central region
- To determine Higgs boson couplings $qq \to qqW^+W^-$ cross sections must be know precisely $\Rrightarrow$ NLO QCD corrections

B. Jäger, C. Oleari, D. Zeppenfeld, JHEP 0607, 015 (2006)

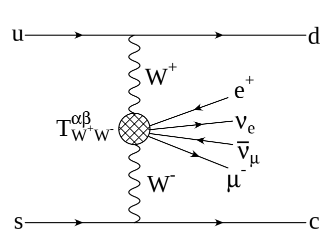
Practical Simplifications

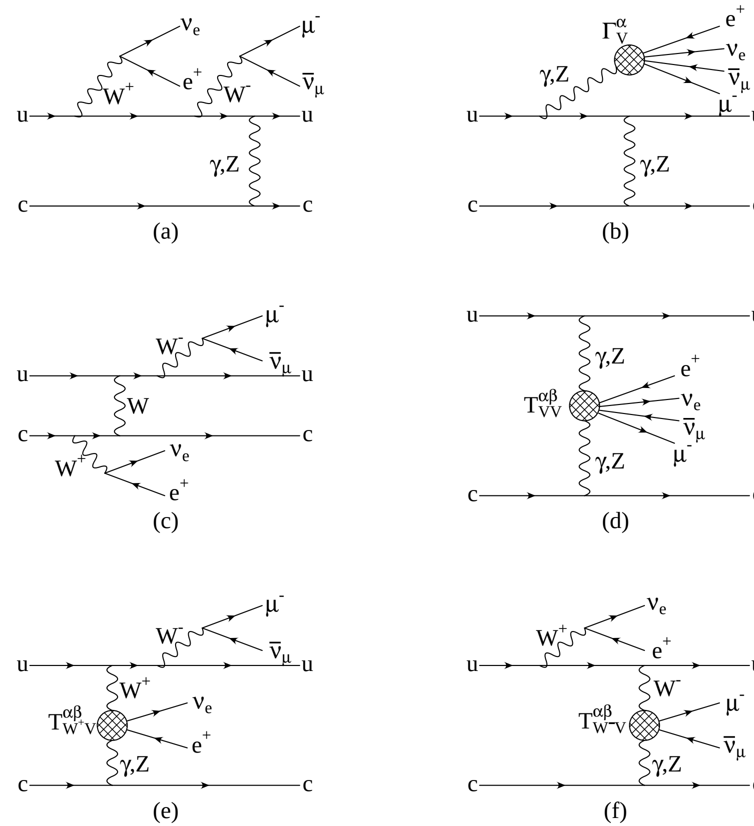


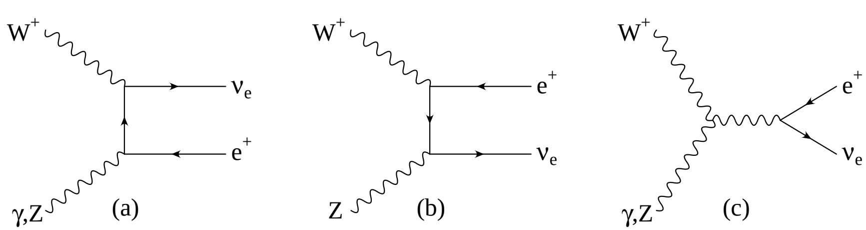
- Single Feynman Diagram for different quark flavors on the two fermion lines
- Any identical fermion effects systematically neglected $\Rrightarrow$ 0.3% at LO
  - $\bar{q}q \to Z^\star \to ZH;\ Z \to \bar{q}q$
  - Interchange of identical quarks in the initial or final state $qq \to qqH, \bar{q}\bar{q} \to \bar{q}\bar{q}H$
- Strongly suppressed by large momentum transfer in the weak boson propagator in the phase space regions where VBF can be observed experimentally
- Colour singlet structure of exchanged weak boson $\Rrightarrow$ no interference between gluons attached to both upper and lower quark lines
- Corrections to a single quark line $\Rrightarrow$ upper line

WW production in VBF

- WW production via VBF with leptonic decays $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu + 2j$
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC $\Rrightarrow$ 181 Feynman diagrams
- CC $\Rrightarrow$ 92 Feynman diagrams







Tools for the Calculation

- Amplitudes are calculated using helicity amplitudes $\Rrightarrow$ HELAS, MADGRAPH
- MC integration $\Rrightarrow$ modified version of VEGAS
- Optimised phase space for up to 7 particles in the final state
- PDF via LHAPDF or build-in CTEQ6m, CTEQ6L1
- No mandatory external libraries
- Parallelised trough the separation of random numbers seeds $\Rrightarrow$ Condor Cluster
- Passarino-Veltman reduction of tensor integrals up to box-type virtual corrections

G. Passarino, M. J. Veltman, Nucl. Phys. B160, 151 (1979)

- Reduction scheme proposed by Denner and Dittmaier for pentagon-type

A. Denner, S. Dittmaier, Nucl. Phys. B658, 175 (2003), B734, 62 (2006)

- Dipol subtraction formalism in the version proposed by Catani and Seymour

S. Catani, M. H. Seymour, Nucl. Phys. B485, 291 (1997)

Performance

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 %

- *LO event files AMD Athlon 64 2.2 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

- *NLO cross sections Intel Centrino 1.8 GHz*

Input & Output

- *Input files*

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

- *Output files*
  - *Histograms: ROOT, Gnuplot, Paw, Topdrawer*
  - *LHA event-files as ASCII files.*

Getting Started

- *Download the code*
  - **http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/**
- *Extract it*
  - **$ tar -zxvf vbfnlo.tar.gz**
- *Adjust the Makefile*
  - *Choose your Fortran compiler* $\Rrightarrow$ **g77**
  - *Enter the library paths, you want to link to e.g. CERNLIB or LHAPDF*
  - *Enable the desired libraries e.g.*

WITH_LHAPDF = 1

WITH_CERNLIB = 0

WITH_ROOT = 1

Configure VBFNLO

- *Adjust* **vbfnlo.dat**
- LaTeX *files are provided in* **./doc/** *to explain the options*
  - *process_list.tex, scales.tex, ew_scheme.tex*
  - *Manual.tex* $\Rrightarrow$ **$ make gv**

PROCESS = 102	*Identifier for process*
LO_ITERATIONS = 4	*Number of iterations at LO*
NLO_ITERATIONS = 4	*Number of iterations at NLO*
LO_POINTS = 22	*Number of points for LO* $\Rrightarrow$ $2^{22} \approx 4 \cdot 10^6$
NLO_POINTS = 22	*Number of points for NLO*
NLO_SWITCH = true	*Switch: NLO/LO calculation*
ECM = 14000d0	*Collider center-of-mass energy*

Configure VBFNLO

ID_MUF = 12	*ID for factorisation scale*
ID_MUR = 12	*ID for renormalisation scale*
XIF = 1d0	*Scale factor xi for mu_F*
XIR = 1d0	*Scale factor xi for mu_R*
ANOM_CPL = false	*Use anomalous couplings*
LHA_SWITCH = true	*Les Houches Accord files only for LO calculation*
UNWEIGHTING_SWITCH = true	*Weighted/unweighted (T/F) events for LHA*
PRENEVUNW = 1000	*Number of events to calculate pre-maximal weight*
TAUMASS = true	*Include mass of the tau lepton(s) in the LHA file*
ROOT = true	*Create root-file*
REPLACE = true	*Replace output files*
ROOTFILE = histograms	*Name of root-file (+ '.root')*

Configure VBFNLO

- *Adjust* **cuts.dat**

RJJ_MIN = 0.8d0	*Minimum jet-jet R separation*
Y_P_MAX = 5.0d0	*Maximum pseudorapidity for partons*
NJET_MIN = 2	*Minimum number of defined jets*

- *Adjust VBF cuts in* **cuts.dat**

ETAJJ_MIN = 4d0	*Minimum rapidity gap size*
YSIGN = true	*Tagging jets* $y_{j_1} \cdot y_{j_2} < 0$
LRAPIDGAP = true	*Leptons fall inside rapidity gap*
MDIJ_MIN = 600d0	*Dijet minimum mass cut on tagging jets*

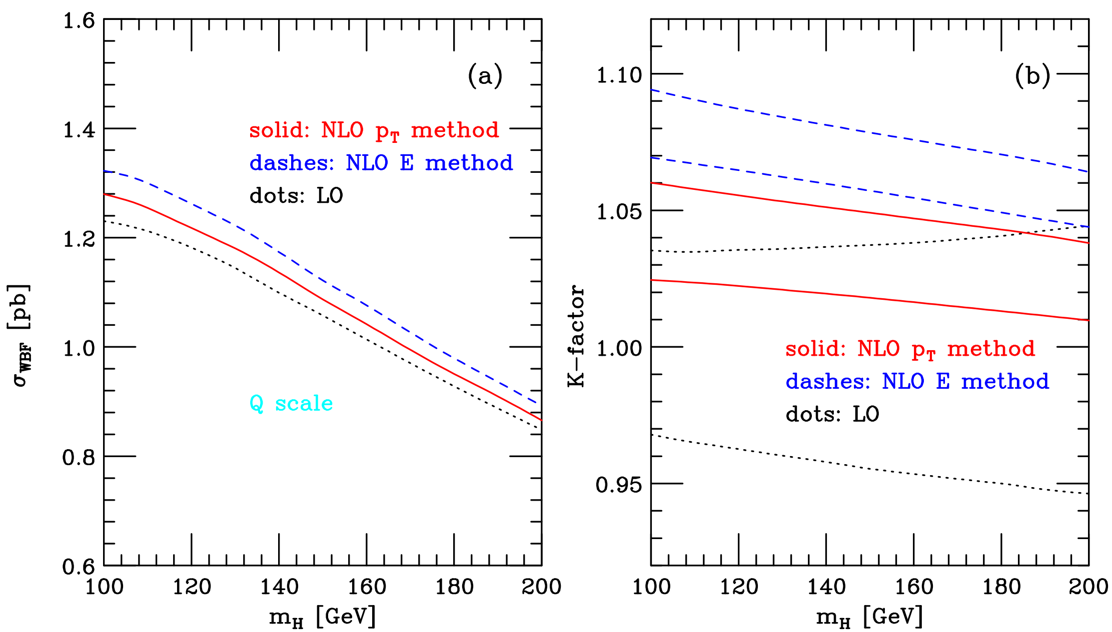
Adding new histogram

- *Add new histogram in* **./src/histograms.F**
  - **call CreateHist(ID, title, bins, min, max)**
  - **real*8 jets(0:7,max_jets), leptons(0:7,max_v), photons(0:7,max_v)**
  - **call FillHist(ID, value, dw, NLO)**
- *As a result you will get histogram for LO and NLO*

- *Recompile* ⇛ **$ make**
- *Run the code* ⇛ **$ make run**
- *Questions, comments, suggestions or bug reports, please e-mail us*
  - **vbfnlo@particle.uni-karlsruhe.de**

$qq \longrightarrow qqH$

- *Higgs boson production cross section via VBF as a function of* m_H
  - *Total cross section within the cuts*
  - *Scale dependence for variation of* μ_R *and* μ_F *by a factor of 2*
- *NLO effects modest* 3%-5% *for* p_T *method,* 6%-9% *for* E_T *method*

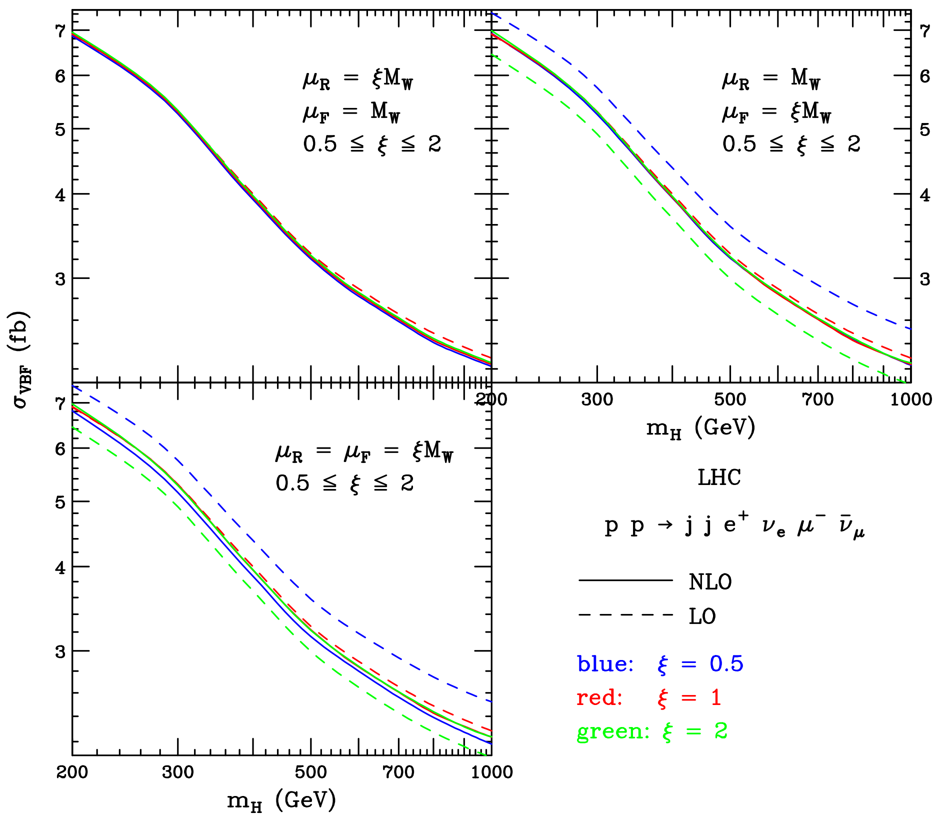


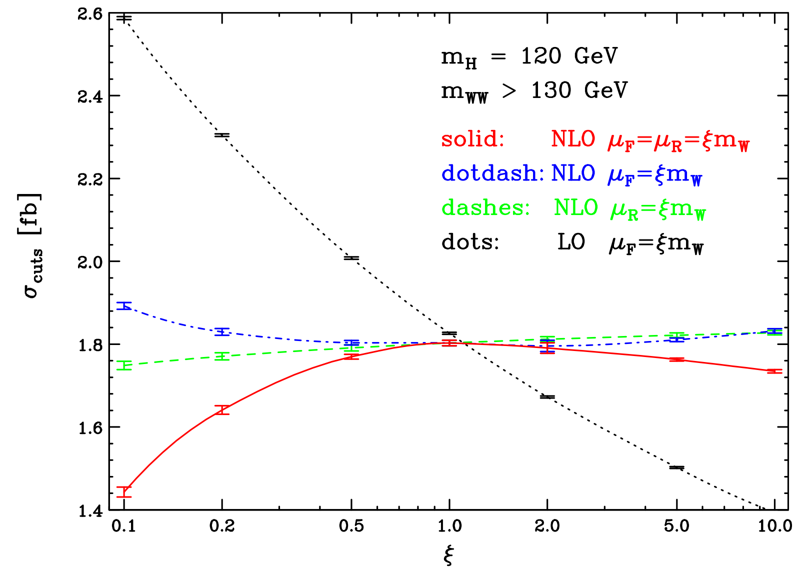
- k_T *algorithm*
- $y_{j_1} < \eta_{l_{1,2}} < y_{j_2}$
- $y_{j_1} \cdot y_{j_2} < 0$
- $\Delta y_{j_1 j_2} = |y_{j_1} - y_{j_2}| > 4$
- *NLO* $\Rrightarrow$ *CTEQ6M*
- *LO* $\Rrightarrow$ *CTEQ6L1*
- $K = \frac{\sigma^{NLO}(\mu_R,\mu_F)}{\sigma^{LO}(\mu_F=Q_i)}$

T. Figi, D. Zeppenfeld, C. Oleari, Phys. Rev. D68, 073005 (2003)

$qq \to qqWW$

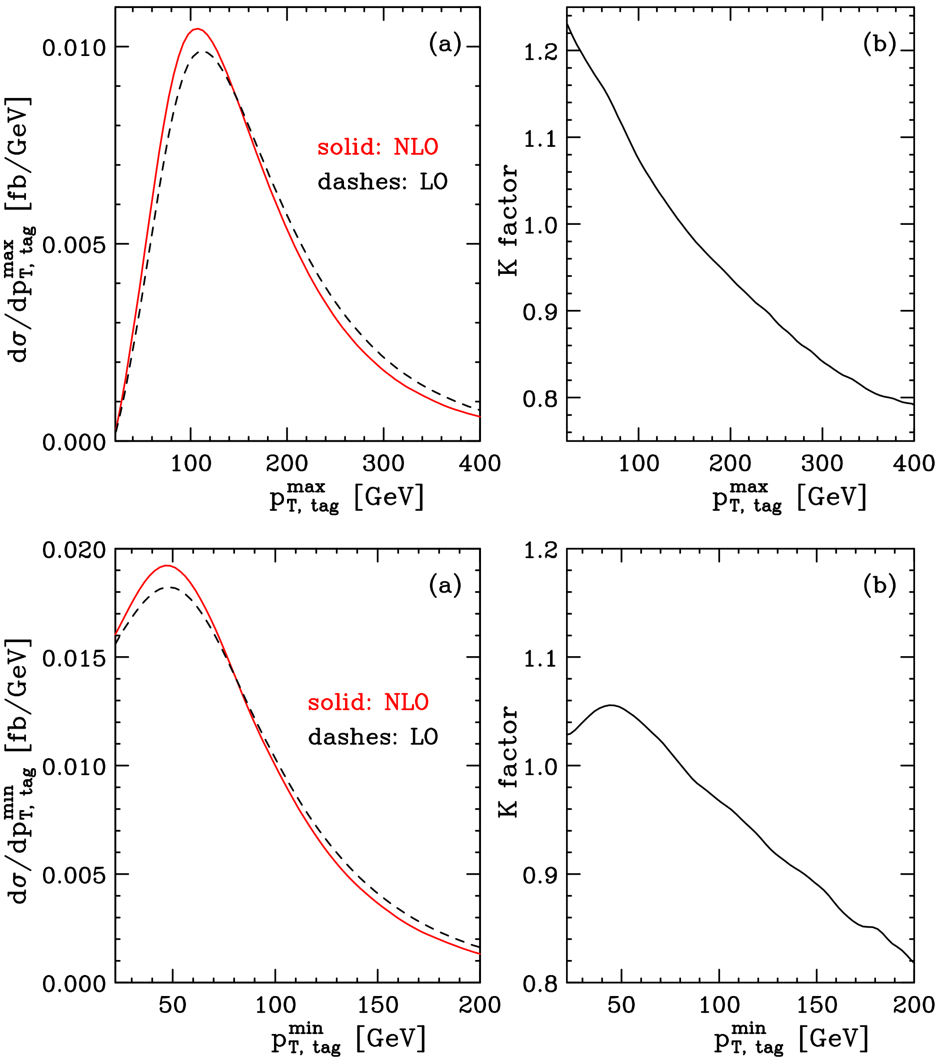
- *Scale dependence of the total cross section without Higgs contribution*
- *Higgs mass dependence of the total cross section*
- *NLO cross section quite insensitive to scale variation* $\Rightarrow$ *changes less then* 2%





B. Jäger, C. Oleari, D. Zeppenfeld, JHEP 07, 015 (2006)

$qq \to qqWW$



B. Jäger, C. Oleari, D. Zeppenfeld, JHEP 07, 015 (2006)

- *Transverse momentum distribution highest and smallest p_T tagging jet*
- $m_H = 120\,GeV$
- $\mu_F = \mu_R = m_W$
- *Dynamic K factor* $K = \frac{d\sigma_{NLO}/dx}{d\sigma_{LO}/dx}$
- *Scale variations between 0.5$\cdot m_W$ and 2$\cdot m_W$ change distributions by 2$\%$ up to 6$\%$ in the tails*
- $p_{T,tag}^{max} \Rrightarrow$ *K=1.2-0.8*
- $p_{T,tag}^{min} \Rrightarrow$ *K=1.1-0.8*

Summary & Outlook

- VBF offers promising prospect for investigation of Higgs properties
- VBFNLO - fully flexible parton level MC program
- Computation of various observables at LO and NLO QCD
- NLO corrections moderate and under theoretical control
- Future processes in VBFNLO
  - $pp \to WZjj \to l^+l^-l\nu jj$
  - $pp \to WWjj \to l\nu jjjj \;\Rrightarrow$ hadronic W decay
  - $pp \to V'jj \;\Rrightarrow$ Kaluza Klein excitations from extra dimensions
  - $pp \to Hjj \;\Rrightarrow$ via gluon fusion at LO

http://www-itp.physik.uni-karlsruhe.de/~vbfnloweb/