VBF Processes at the LHC with VBFNLO

Malgorzata Worek

ITP Karlsruhe

Mini-Workshop Massive Particle Production at the LHC

30th - 31th October 2007

Outline of the Talk

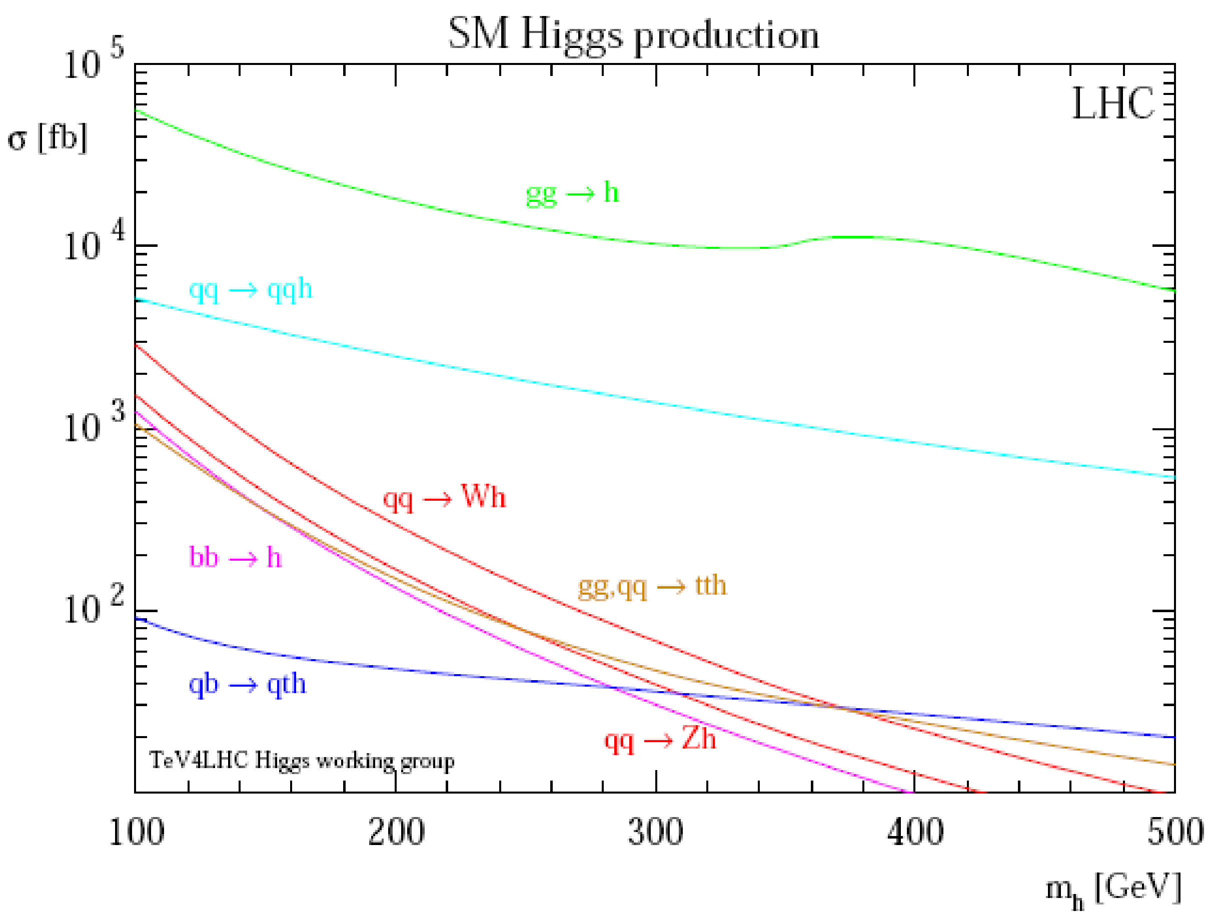
- Introduction & Motivation
- VBF Processes at the LHC
- Methods for the calculations
- VBFNLO
- Results for qqH/qqW/qqZ and qqWW
- Comparison
- Summary & Outlook

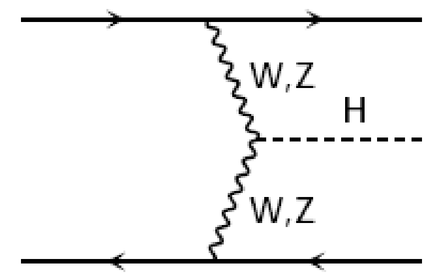
VBFNLO Group:

D. Zeppenfeld at. al. ITP Group of Karlsruhe University
T. Figy, B. Jager, C. Oleari

Higgs Production in VBF

- Physics program of two main LHC experiments ATLAS and CMS aims at the discovery of the Higgs boson - the last missing particle predicted by SM
- Cross sections for Higgs boson production at the LHC
- VBF- quarks scattering via t-channel exchange of W,Z with H radiated off W,Z



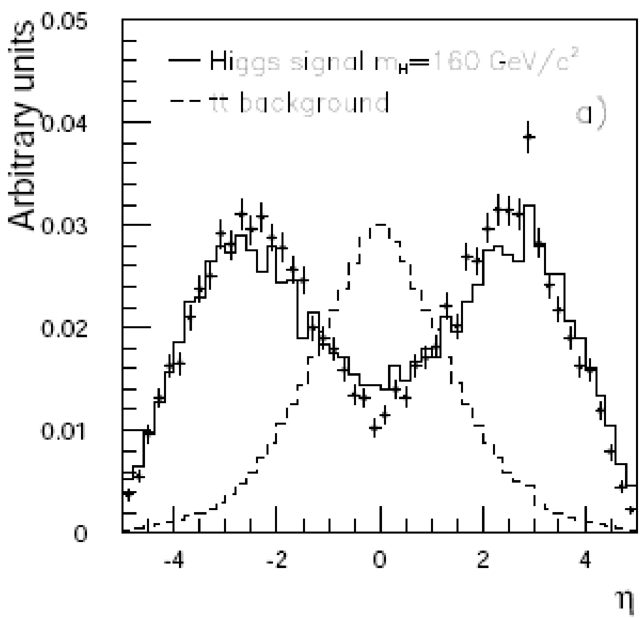


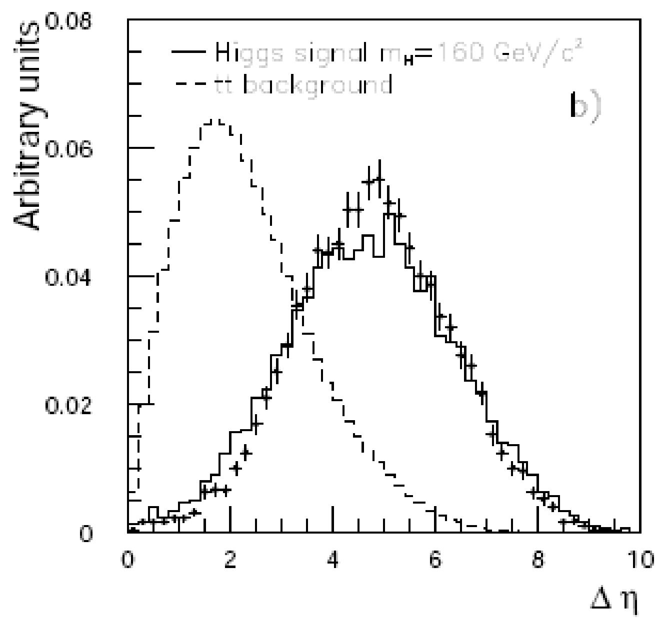
- Rate an order of magnitude smaller then gluon fusion
- Distinctive kinematics and QCD properties - easy to suppress backgrounds for all Higgs boson channels

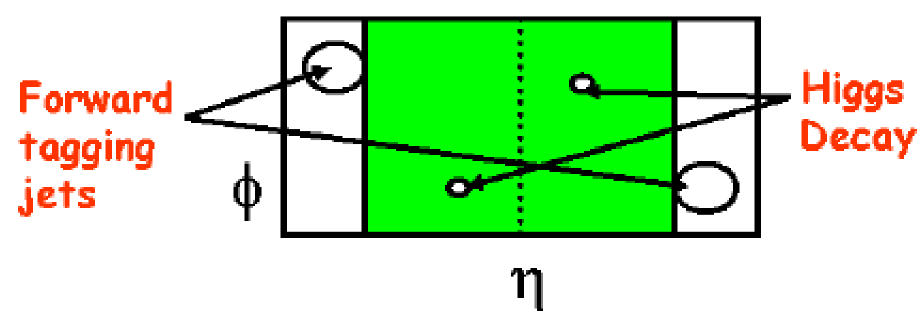
T. Hahn, S. Heinemeyer, F. Maltoni, G. Weiglein, S. Willenbrock arXiv:hep-ph/0607308

Experimental Signature

- Energetic jets in forward and background direction pT > 20 GeV
- Large rapidity separation and large invariant mass of 2 tagging jets
- Higgs decay products between tagging jets
- Little gluon radiation in central rapidity region due to colourless W/Z exchange







D. Rainwater arXiv:hep-ph/0702124

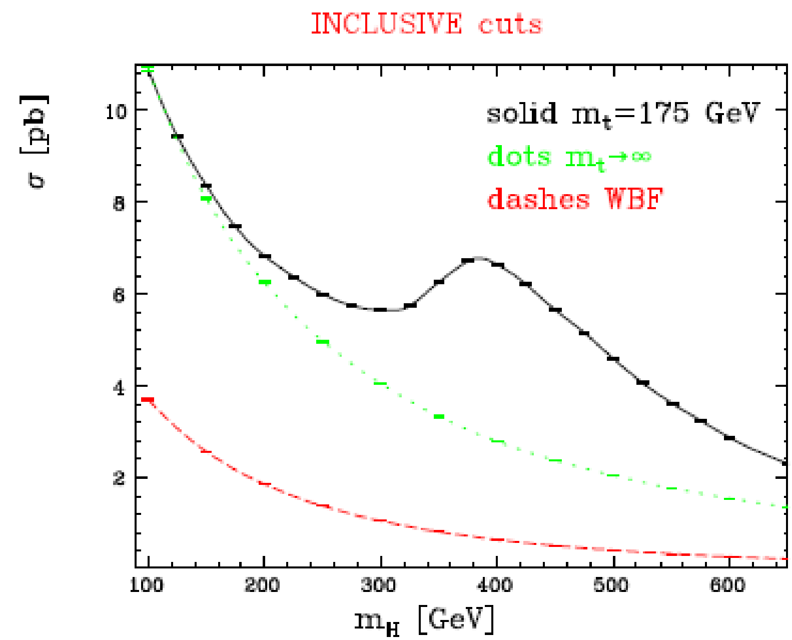
Tagging Jets Selections for VBF

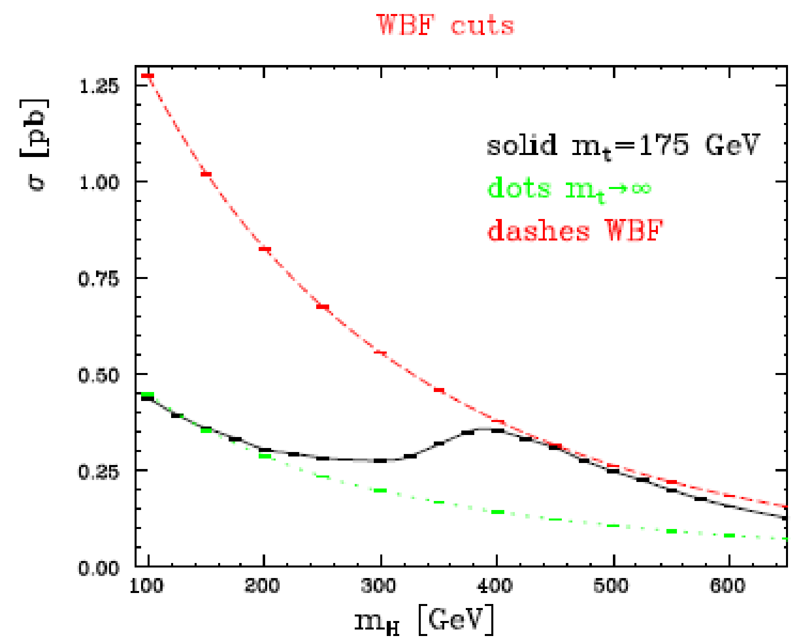
- Production of Higgs accompanied by 2 jets via gluon fusion
- H+2jets cross section at the LHC as a function of m_H
- Inclusive cuts

$$p_{T_j} > 20\,GeV$$
$$|\eta_j| < 5$$
$$\Delta R_{jj} > 0.6$$

- Typical tagging jet selections for VBF

$$|\eta_{j_1} - \eta_{j_2}| > 4.2$$
$$\eta_{j_1} \cdot \eta_{j_2} < 0$$
$$m_{jj} > 600\,GeV$$



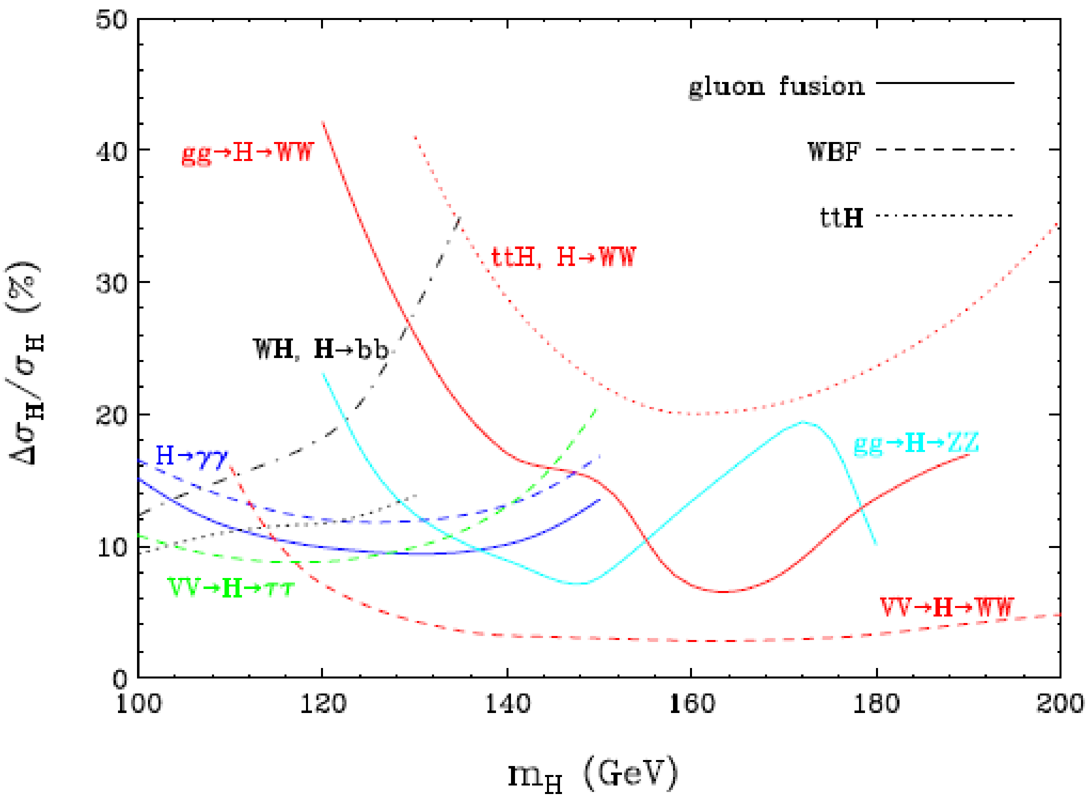


V. Del Duca, W. Kilgore, C. Oleari, C. Schmidt, D. Zeppenfeld Phys. Rev. Lett. 87 (2001) 122001

Higgs Boson Couplings at the LHC

- Double jets tagging and central jet veto used to suppress QCD backgrounds
- Allows precise measurement of Higgs couplings – HWW, HZZ, Hff
- At the LHC with statistical accuracies on $\sigma \cdot BR$ of order 10% for VBF

D. Zeppenfeld, R. Kinnunen, A.. Nikitenko, E. Richter-Was Phys. Rev. D62 (2000) 013009D. Zeppenfeld arXiv:hep-ph/0203123



Expected relative error on determination of $\sigma \cdot BR$ for various Higgs boson search channels with 200 fb^{-1} of data

Lowest errors are achievable in VBF production of Higgs

Precise prediction are required – NLO QCD corrections !!!

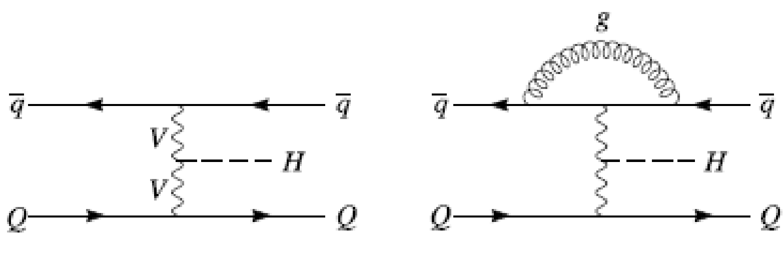
VBF Processes at the LHC

- $qq \to qqH$ T. Figy, C. Oleari, D. Zeppenfeld (2003)
  E. L. Berger, J. Campbell (2004)
  M. Ciccolini, A. Denner, S. Dittmaier (2007)
  - Higgs coupling measurements
- $qq \to qqZ$, $qq \to qqW$ C. Oleari, D. Zeppenfeld (2004)
  - Similar features as for Higgs production - Irreducible background
  - $Z \to \tau\tau$ as background for $H \to \tau\tau$
  - Measure central jet veto acceptance at the LHC
- $qq \to qqWW$, $qq \to qqZZ$, $qq \to qqWZ$ B. Jager, C. Oleari, D. Zeppenfeld (2006)
  G. Bozzi, B. Jager, C. Oleari, D. Zeppenfeld (2007)
  - Between 15% and 3.5% of the Higgs signal for $115\ \mathrm{GeV} < M_H < 160\ \mathrm{GeV}$
  - qqWW is a background to $H \to WW$ in VBF
  - Underling process in weak boson scattering $WW \to WW$, $WW \to ZZ$, $WZ \to WZ$

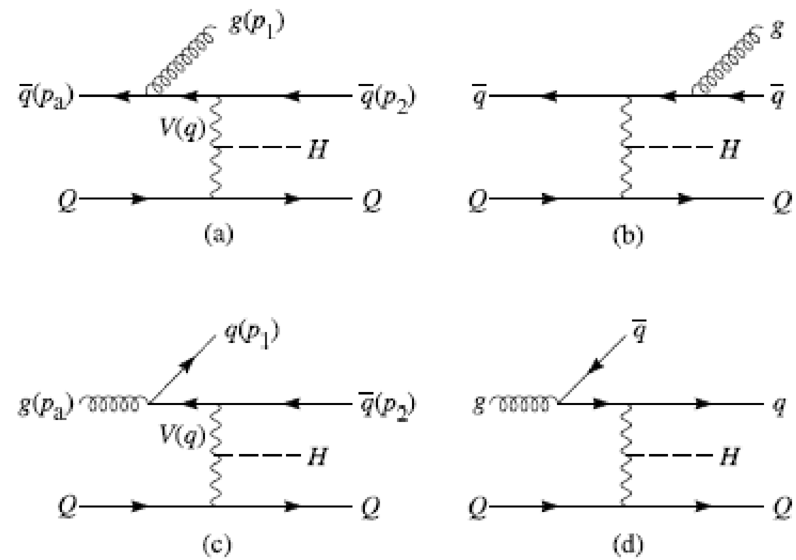
Generic Features for VBF

No t-channel gluon exchange at NLO

QCD corrections to a single quark line !



Born and vertex corrections



Real emission contributions

- Any identical fermion effects systematically neglected – 0.3% at LO
- s-channel exchange $q\bar{q} \rightarrow Z^* \rightarrow ZH; Z \rightarrow q\bar{q}$
- Interchange of identical quarks in the initial and final state $qq \rightarrow qqH; \bar{q}\bar{q} \rightarrow \bar{q}\bar{q}H$
- Strongly suppressed by large momentum transfer in weak boson propagator in phase space regions where VBF can be observed experimentally
- Colour singlet structure of exchanged weak boson – no interference between gluons attached to both upper and lower lines
- QCD corrections to different quark lines are independent

Calculations

- Amplitudes are calculated using helicity amplitudes

K. Hagiwara D. Zeppenfeld Nuvl. Phys. B274 (1986) 1

K. Hagiwara, d. Zeppenfeld Nucl. Phys. B313 (1989) 560

- MC integration by modified version of VEGAS
- Optimised phase space for up to 7 particles in the final state
- Passarino-Veltman reduction of tensor integrals up to box-type virtual corrections

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

- Reduction scheme proposed by Denner and Dittmaier for pentagon-type for $qq \to qqWW$, $qq \to qqZZ$, $qq \to qqWZ$

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

- Calculation for real emission is done by using dipole subtraction formalism in the version proposed by Catani and Seymour

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

VBFNLO

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

- Parton level MC for VBF processes at NLO QCD
- Arbitrary cuts and distributions can be implemented
- Various scale choices
- CTEQ6L1 and CTEQ6m PDF sets build-in
- LHAPDF
- Cross sections at LO and NLO QCD
- Differential distributions at LO and NLO
- Anomalous HVV couplings both in the production and decay of the Higgs boson
- Anomalous triple couplings in WWjj
- K-Factors and differential K-Factors
- Weighted/Unweighted events
- LHA event files
- Histograms: Root, Gnuplot, Paw, Topdrawer
- Fortran 77

$$pp \to Hjj$$

$$pp \to Hjj\,, \quad H \to \tau\tau$$

$$pp \to Hjj\,, \quad H \to \gamma\gamma$$

$$pp \to Hjj\,, \quad H \to b\bar{b}$$

$$pp \to Hjj\,, \quad H \to WW \to l\nu l\nu$$

$$pp \to Hjj\,, \quad H \to ZZ \to 4l\,, 2l2\nu$$

$$pp \to WWjj \to l\nu l\nu\, jj$$

$$pp \to ZZjj \to 4l\, jj$$

$$pp \to ZZjj \to 2l\,2\nu\, jj$$

$$pp \to W^{\pm}\, jj \to l\nu\, jj$$

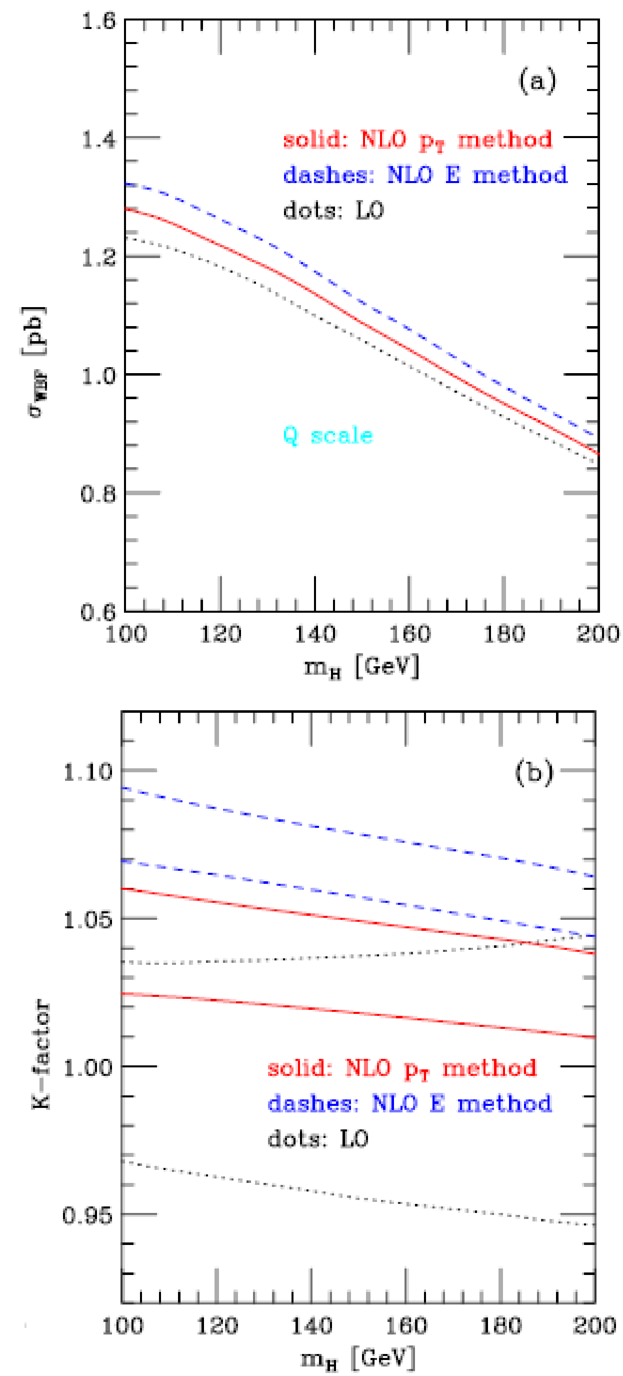
$$pp \to Zjj \to 2l\, jj$$

Results for Higgs Production

- m_H=120 GeV
- p_T and E_T methods for tagging jets
- NLO effects modest
  - 3%-5% for p_T method
  - 6%-9% for E_T method
- Residual scale uncertainty
  - 5% at LO
  - 2% at NLO
- QCD corrections under excellent control
- Electroweak corrections are needed

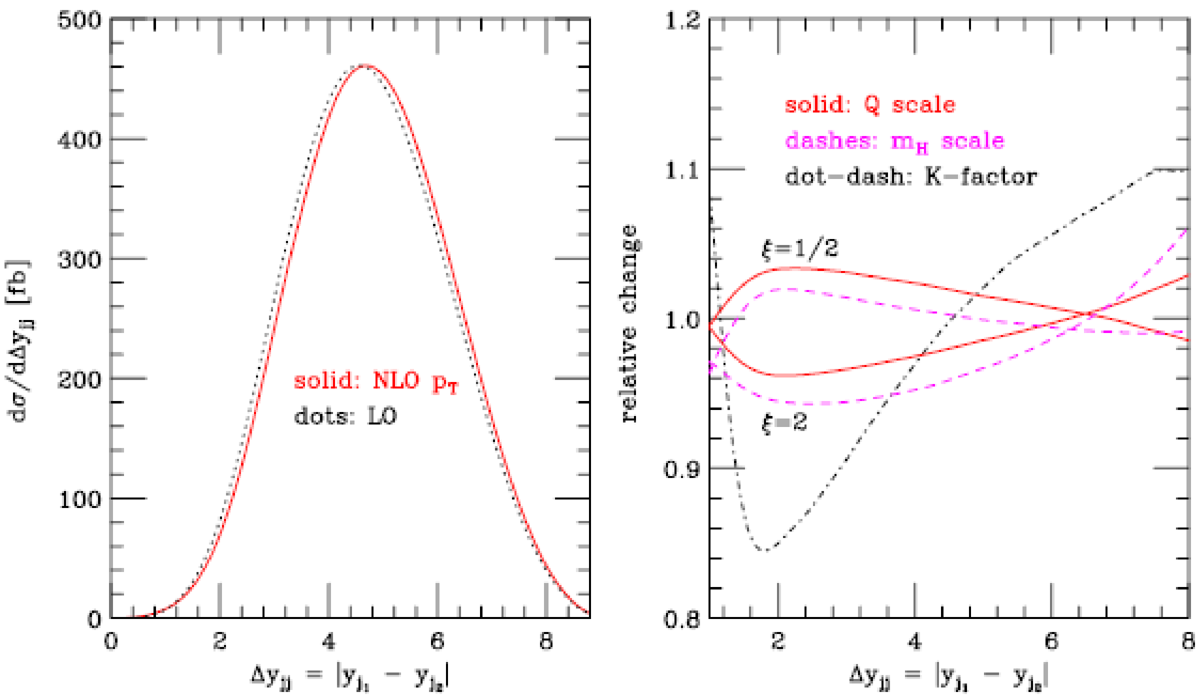
  Solved now !

→ talk by A. Denner



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

Results for Higgs Production



Wide separation of tagging jets important for rejection of QCD background survive at NLO

Dynamic K factor: 1.1 - 0.85

Scale dependence of NLO result 5% for distribution

- Rapidity separation of two tagging jets
- Left hand panel dσ/dΔyjj in fb
- Right hand panel:
  - K-factor
  - Scale variation of the NLO results

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

Comparison between VBF QCD Calculations

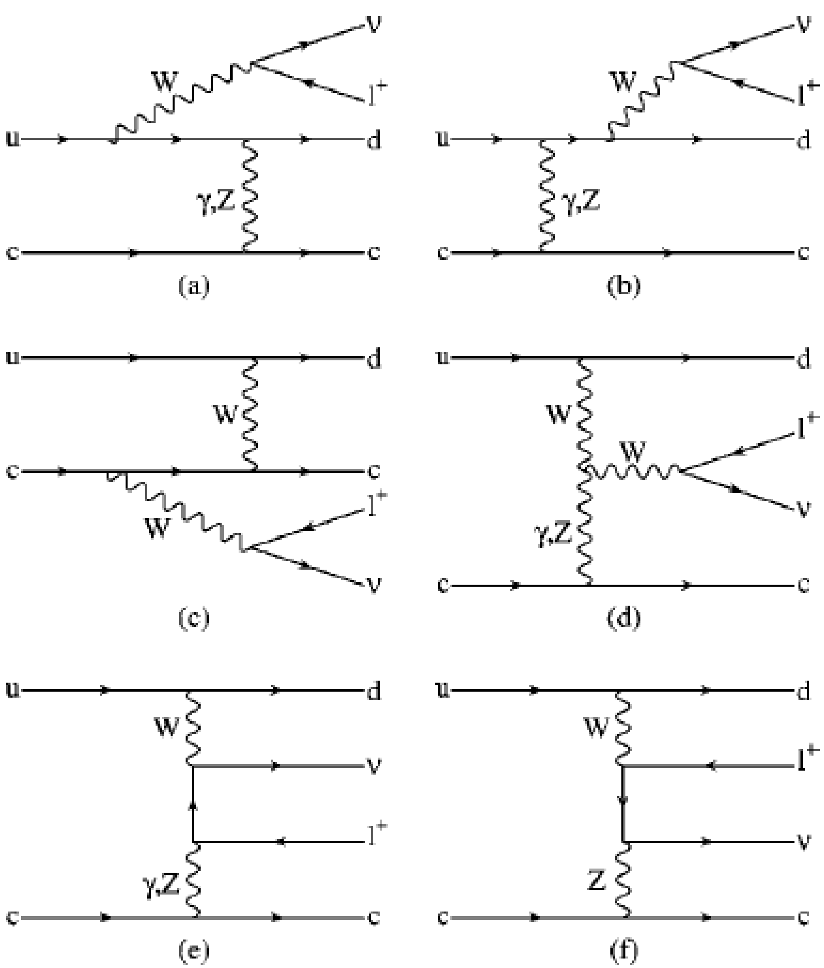
- Excellent agreement between QCD corrections from Denner (et al) and Zeppenfeld (et al) for pp→hjj at LO and NLO QCD
- CTEQ6L1 PDFs for LO σ's, CTEQ6M for NLO σ's, VBF cuts

Cross Section for pp→hjj in fb

Process	Denner et al	VBFNLO	Ratio-1
M_h=120 GeV, LO M_h=120 GeV, NLO	1647 1745	1650 1740	-0.17 ± 0.10% 0.27 ± 0.13%
M_h=160 GeV, LO M_h=160 GeV, NLO	1299 1398	1300 1397	-0.14 ± 0.07% 0.05 ± 0.1%
M_h=200 GeV, LO M_h=200 GeV, NLO	1035 1131	1035 1128	0.04 ± 0.06% 0.26 ± 0.10%

Single W Production

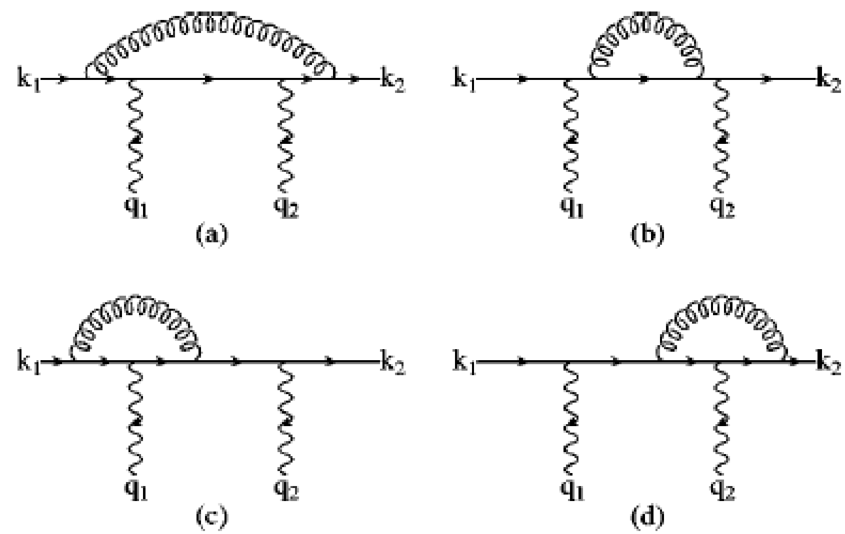
- Seven Feynman graph topologies contribute at tree level



Additional bremsstrahlung graph with the vector boson emitted of the final state charm quark - mirror image of graph (b)

10 → Feynman diagrams for W

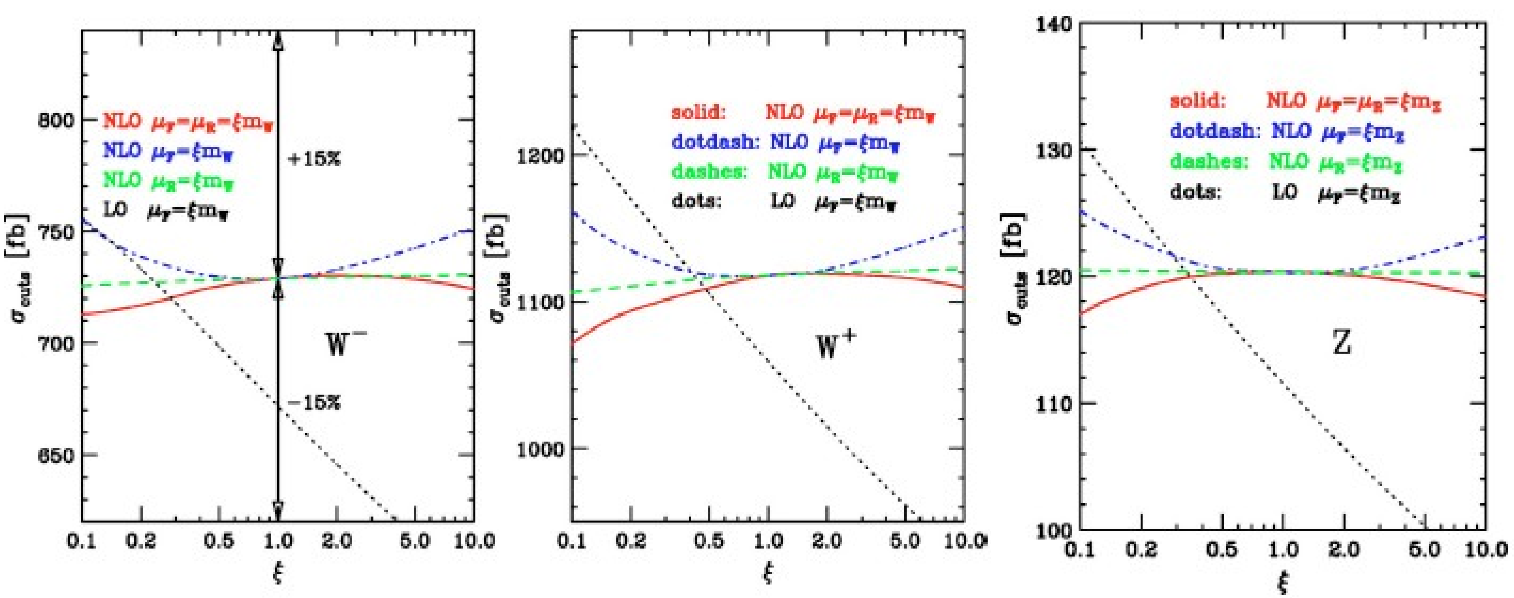
24 → Feynman diagrams for Z



Virtual corrections for a fermion line with two attached electroweak boson - boxline corrections

Results for W and Z Production

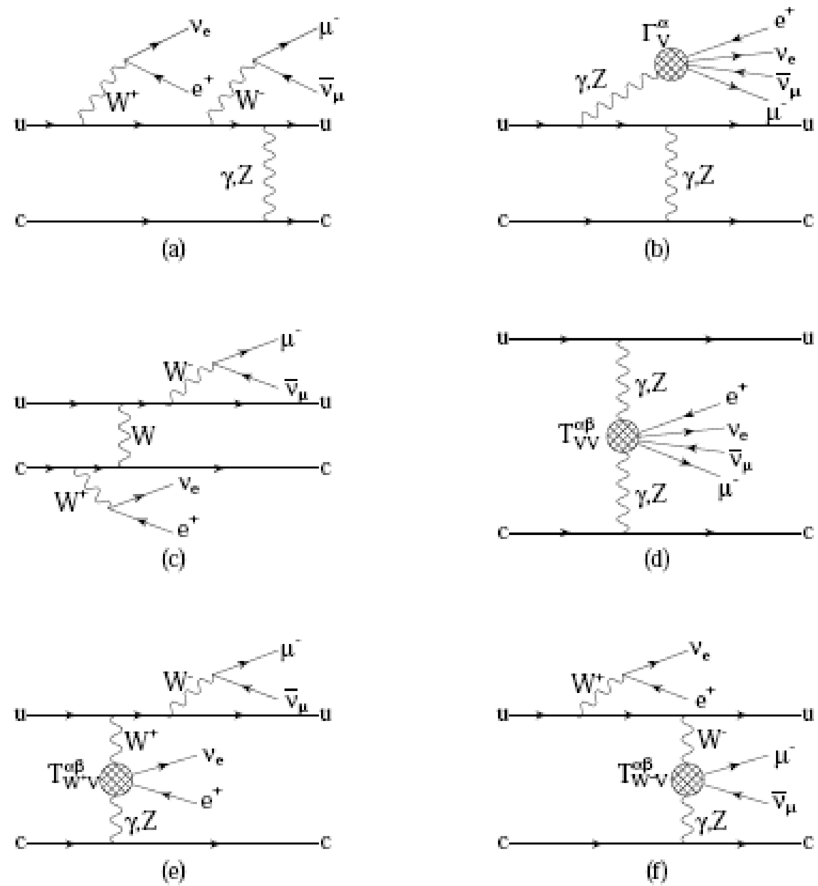
- QCD corrections modest ~10%
- Scale dependence of the total cross section at LO and NLO
- Factorisation scale dependence of LO result is sizeable
- NLO cross sections are quite insensitive to scale variations
- For $0.5 < \xi < 2$ NLO cross sections change by less than 1% in all cases
- Residual NLO scale dependence of about 1%-2% for distributions

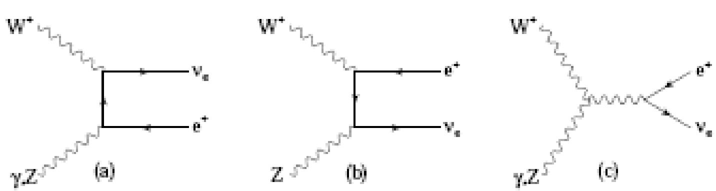


C. Oleari, D. Zeppenfeld Phys. Rev. D69 (2004) 093004

WW Production

- WW production via VBF with leptonic decays
- Spin correlations of the final state leptons
- All resonant and non-resonant Feynman diagrams included
- NC ➡ 181 Feynman diagrams at LO
- CC ➡ 92 Feynman diagrams at LO
- Modular structure – grouping whole set of diagrams. Leptonic tensors do not depend on the quark flavour





- Calculated once reuse in different processes
- Speedup factor ~ 70 compared to MadGraph for real emission corrections

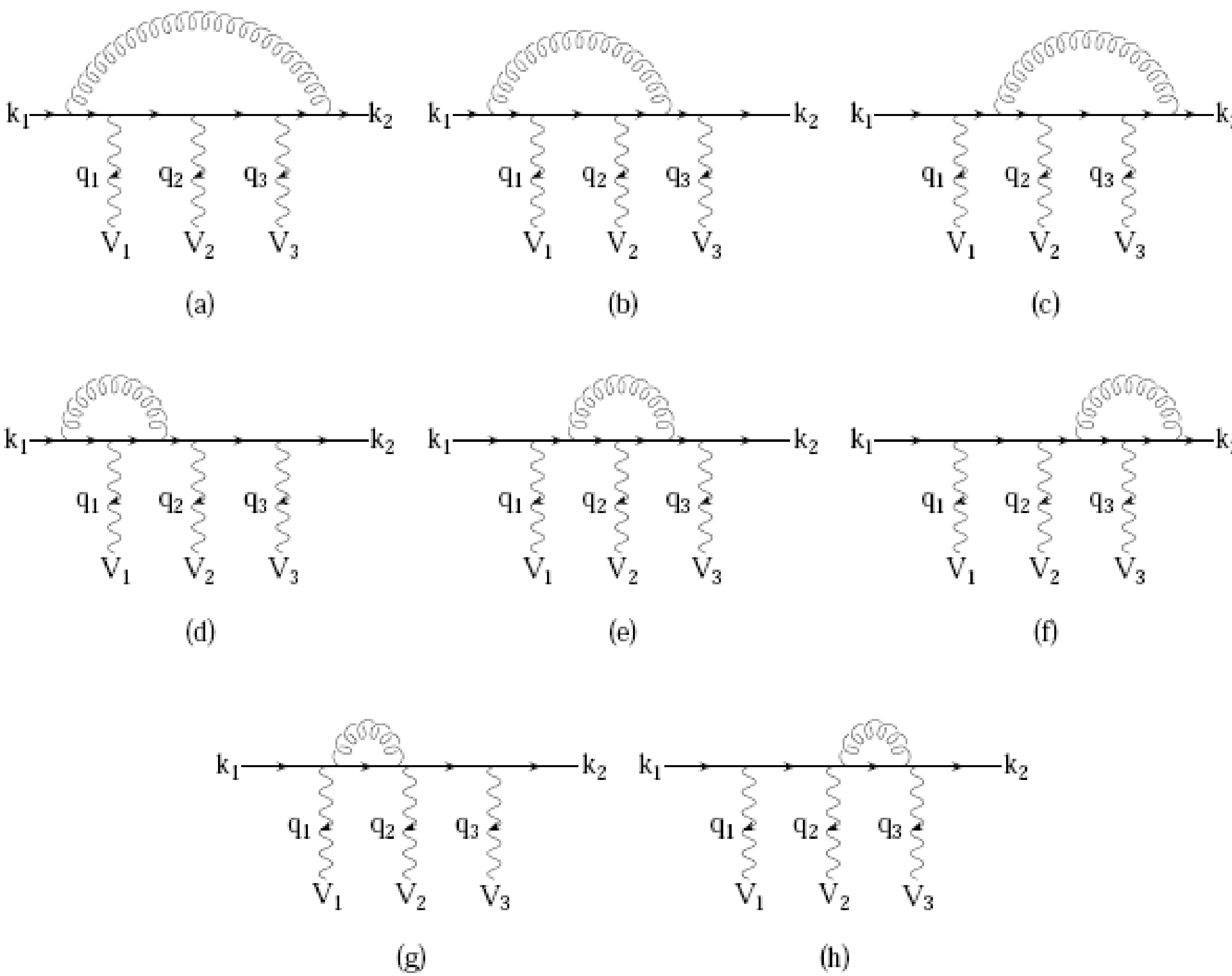
Straightforward inclusion of new physics effects in electroweak sector – only leptonic tensors have to be modified

- Anomalous gauge boson couplings
- Extra Vector Bosons

➡ talk by Ch. Englert

WW Production

- Virtual corrections for a fermion line with three attached vector bosons
- Virtual corrections involve up to pentagons



In PV tensor reduction procedure Gram determinants appear in the denominators of PV coefficient functions

Pentagons: phase space points where these determinants small

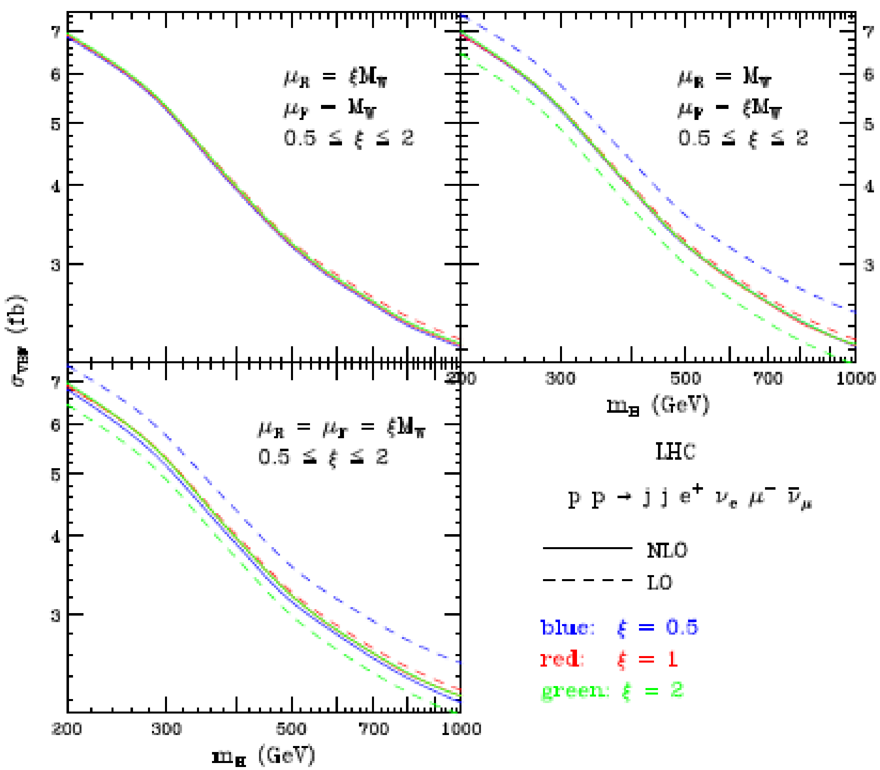
numerical results become unstable

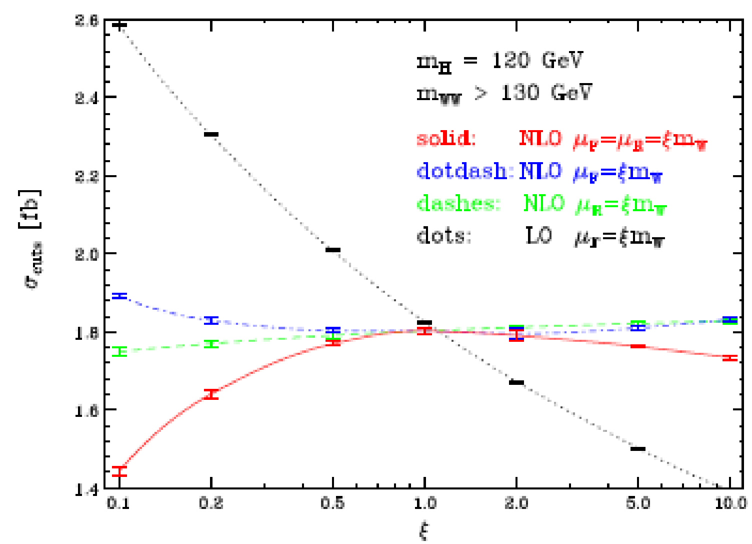
Fraction of events for which numerical instabilities lead to violations of Ward identities 10%

Brought down to 1‰ level with Denner-Dittamier tensor reduction scheme

Results for WW Production

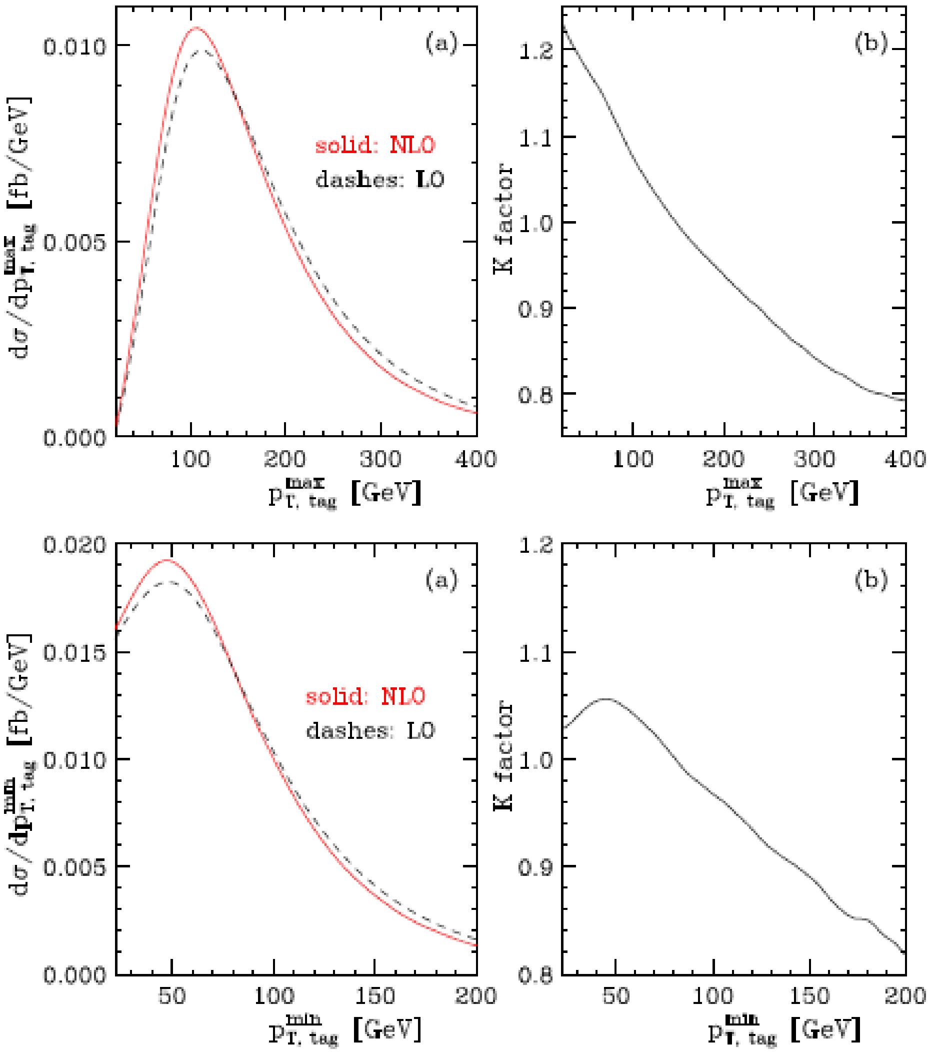
- QCD corrections modest changing total cross section by less then 10%
- Scale dependence of the total cross section without Higgs contribution
- Higgs mass dependence of total cross section
- NLO cross section quite insensitive to scale variation - changes less then 2%





B. Jager, C. Oleari, D. Zeppenfeld JHEP07 (2006) 015

Results for WW Production



- Transverse momentum distribution of highest and smallest p_T tagging jet

$$m_H = 120 \quad GeV$$
$$\mu_F = \mu_R = m_W$$

- Dynamic K-Factor varying between 1.2 – 0.8 as p_T^{max} increases from 20 GeV to 400 GeV
- For p_T^{min} – effect is slightly smaller

B. Jager, C. Oleari, D. Zeppenfeld JHEP07 (2006) 015

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

Summary & Outlook

- VBF Processes important for the LHC - allow precise measurements of the HWW, HZZ, Hff couplings
- Experimental accuracy 5%-10%
- NLO QCD corrections moderate and under theoretical control
- VBNLO - NLO parton level MC for VBF and dominant backgrounds
- Includes Hjj, Zjj, Wjj, WWjj, ZZjj at NLO with decays
- Input: Arbitrary cuts, scale choices, PDF functions
- Output: arbitrary differential distributions
- Can include (resource for BSM group):
  - anomalous HVV couplings
  - anomalous WWW couplings