Karlsruhe Institute of Technology

Computational Theoretical Particle Physics
SFB TR9

VBFNLO

Michael Rauch | May 2011

INSTITUTE FOR THEORETICAL PHYSICS

Introduction

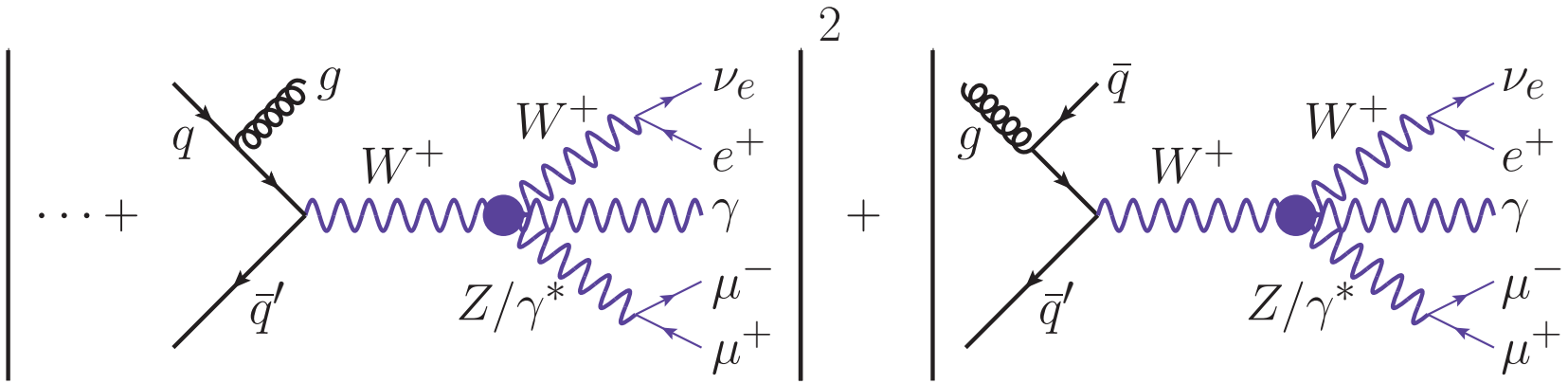
VBFNLO

- Parton-level Monte Carlo for processes with electroweak bosons
  - vector-boson fusion production at NLO QCD of
    - Higgs (+NLO EW, NLO SUSY)
    - Higgs plus third hard jet
    - Higgs plus photon
    - vector boson (W,Z,γ)
    - two vector bosons (WW, WZ, ZZ)
  - diboson & diboson plus hard jet (NLO QCD)
  - triboson (NLO QCD)
  - Higgs plus two jets via gluon fusion (one-loop LO)
- new physics models
  - anomalous Higgs couplings
  - anomalous triple and quartic couplings
  - Higgsless models
- 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)
- event files in Les Houches Accord (LHA) format (LO only)

Implementation Details

- Helicity amplitude method
- 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)

[Hagiwara, Zeppenfeld]



- Catani-Seymour dipole subtraction scheme

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

- 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

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  $\Rightarrow$ Efficiently suppresses fragmentation contribution

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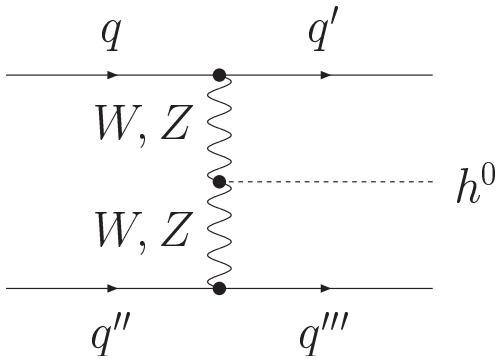
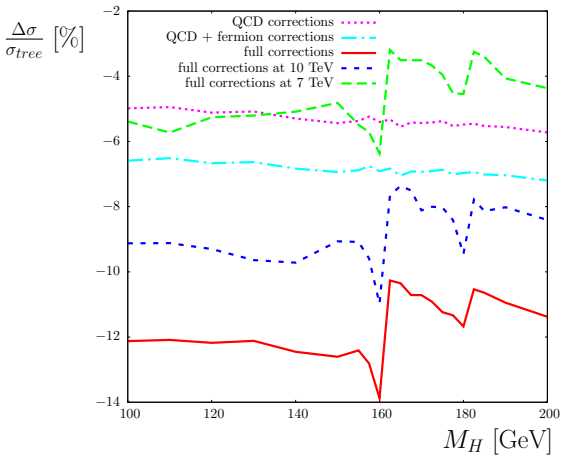
Vector-boson-fusion Higgs

[New in VBFNLO v2.5]

[Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; Campbell, Ellis, Berger]





- Clear signature due to two tagging jets
- QCD corrections relatively small $\sim 5\%$
- EW corrections of same size
  [Ciccolinni, Denner, Dittmaier; Figy, Palmer, Weiglein]
- SUSY (QCD+EW) corrections
  [Hollik, Plehn, MR, Rzehak; Figy, Palmer, Weiglein]
- available for all Higgs bosons (h^0, H^0, A^0)
- CP-conserving and -violating scenario

- Higgs boson decays in narrow-width approximation
- For $H \to WW/ZZ \to 4\ell$ full spin information and off-shell effects included

- (parts of NNLO QCD calculation also available)
  [Harlander, Vollinga, Weber; Bolzoni, Maltoni, Moch, Zaro]

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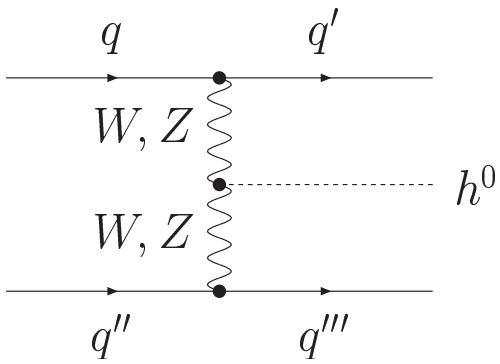

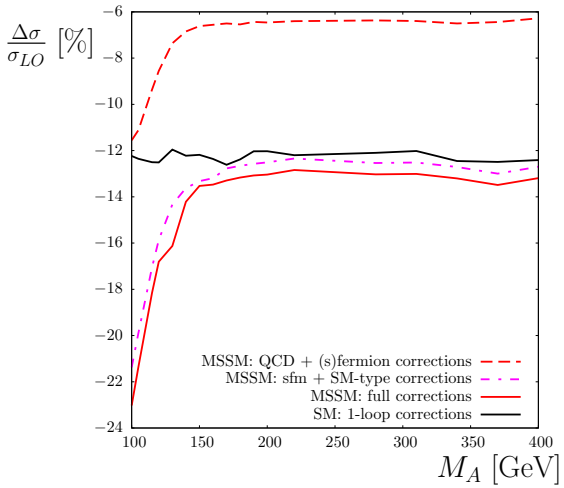

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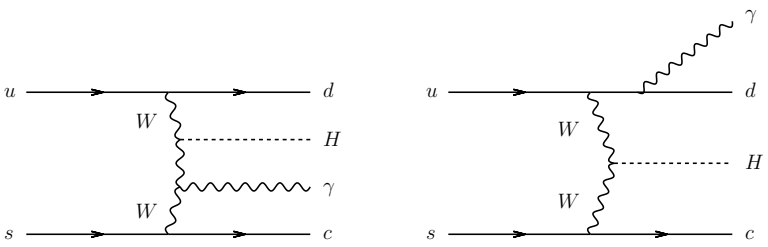
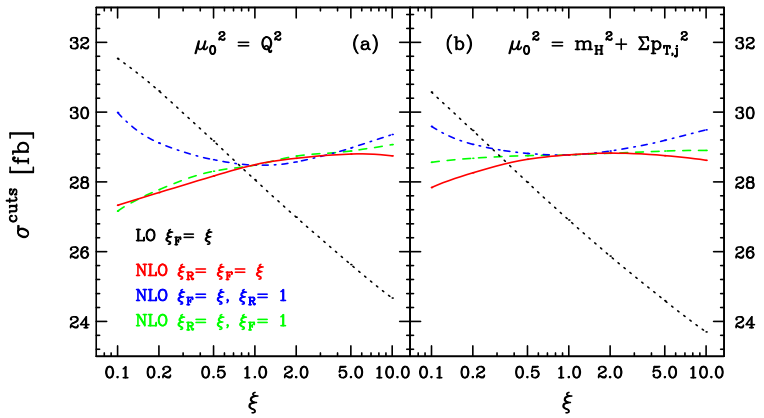
Vector-boson-fusion Higgs plus photon

[New in VBFNLO v2.5]

Additional photon suppresses QCD backgrounds [Gabrielli et al.; Arnold, Figy, Jäger, Zeppenfeld]

Interference between photon emission off initial- and final-state quarks:
neutral t-channel boson (g, Z): destructive
charged t-channel boson (W): constructive

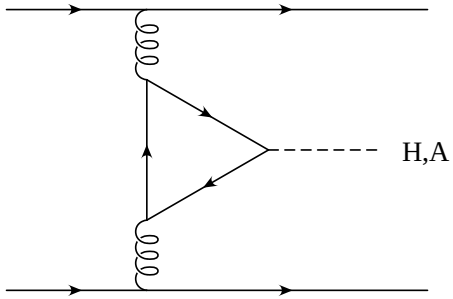


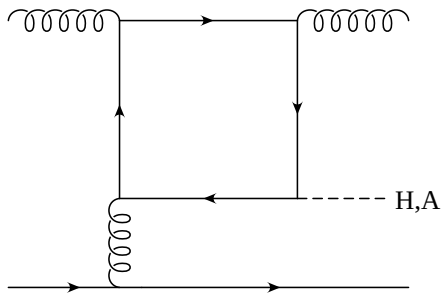


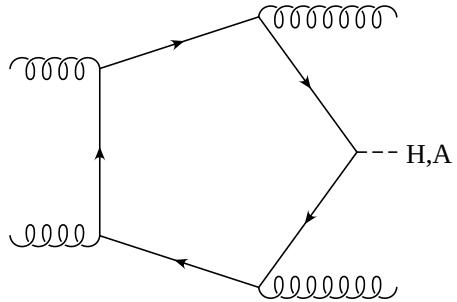
- signal:
  $\sigma_{H\gamma jj} / \sigma_{Hjj} \sim 1/100$
- background:
  $\sigma_{H\gamma jj} / \sigma_{Hjj} \sim 1/3000$
- $\Rightarrow \left. \frac{S}{\sqrt{B}} \right|_{H\gamma jj,\ 100\ \mathrm{fb}^{-1}} \sim 3$
- effect of NLO QCD corrections on relevant distributions small
- scale dependence strongly reduced

Gluon-fusion Higgs

[New in VBFNLO v2.5]







- 2 additional jets to $gg \to H$ can fake VBF signal
- complete LO calculation in the SM [Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld]
  in a generic Two-Higgs doublet model [Campanario, Kubocz, Zeppenfeld]
  and in the (complex) MSSM (squark loops still missing)
- CP-even, CP-odd and arbitrary CP-mixing Higgs implemented
- full top and bottom mass dependence, consistent bottom-quark mass treatment
- Higgs decay (narrow-width approximation)
- numerical stability improved
- VBF-GF interference completely negligible [Georg; Andersen, Smillie; Bredenstein, Hagiwara, Jäger]
- (NLO QCD in $m_t \to \infty$ limit) [Campbell, Ellis, Zanderighi]
- $\to$ CP determination from $\Delta\Phi_{jj}$ [Klämke, Plehn, Rainwater, Zeppenfeld]

Triboson production

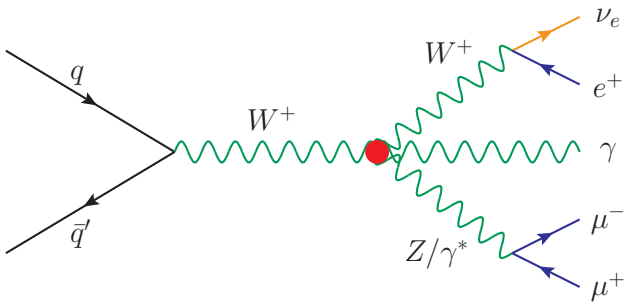
Les Houches experimentalists' wishlist (2005)

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
4. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
5. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
6. $pp \to V + 3$ jets	various new physics signatures
7. $pp \to V\,V\,V$	SUSY trilepton

Triboson processes:

- background to new-physics searches
  $\to$ signature: multilepton + missing E_T
- test triple and quartic anomalous gauge couplings (e.g. $WWZ\gamma$, $WW\gamma\gamma$)
- leptonic decays of weak bosons, all off-shell effects, spin correlations
- full $H \to ZZ$ and $H \to WW$ contributions

e.g. $pp \to W^+Z\gamma \to \ell_1^+\nu_1\ell_2^+\ell_2^-\gamma$



Triboson production

All combinations $V \in \{W^\pm, Z, \gamma\}$ implemented:

- (ZZZ production (no leptonic decays, no Higgs contribution)) [Lazopoulos, Melnikov,Petriello]
- W^+W^-Z production [Hankele, Zeppenfeld]
- (ZZZ, W^+W^-Z, $ZZW^\pm$, $W^\pm W^\mp W^\pm$ (no leptonic decays, no Higgs contributions)) [Binoth, Ossola, Papadopoulos, Pittau]
- $ZZW^\pm$, $W^\pm W^\mp W^\pm$ [Campanario, Hankele, Oleari, Prestel, Zeppenfeld]
- ZZZ
- $W^+W^-\gamma$, $ZZ\gamma$ [Bozzi, Campanario, Hankele, Zeppenfeld]
- $W^\pm Z\gamma$ [Bozzi, Campanario, MR, Rzehak, Zeppenfeld]
- ($W^\pm\gamma\gamma$ production (no leptonic decays, including fragmentation)) [Baur, Wackeroth, Weber]
- $W^\pm\gamma\gamma$ [Bozzi, Campanario, MR, Zeppenfeld]
- $Z\gamma\gamma$, $\gamma\gamma\gamma$ [Bozzi, Campanario, MR, Zeppenfeld]

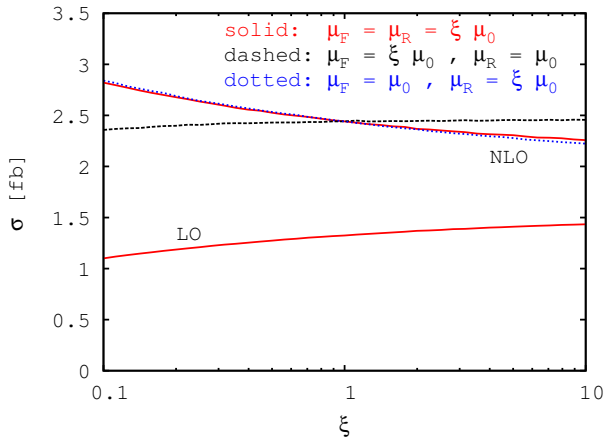
Approximations:

- fermion mass effects neglected
- CKM matrix effects neglected
- Interference terms due to identical particles in the final state neglected

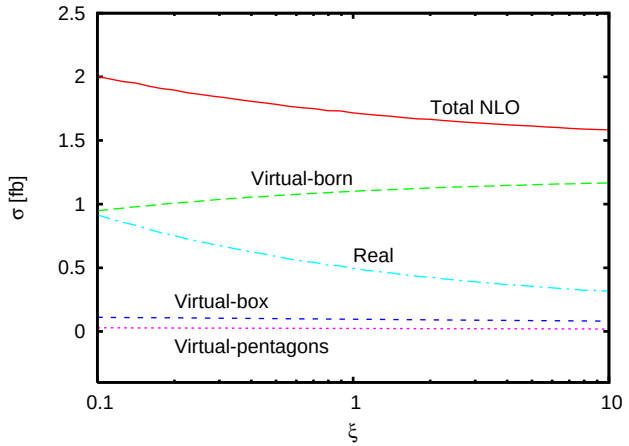
$W^{\pm}Z\gamma$ distributions

Scale dependence

$W^{+}Z\gamma$ ($\mu_0 = m_{WZ\gamma}$)

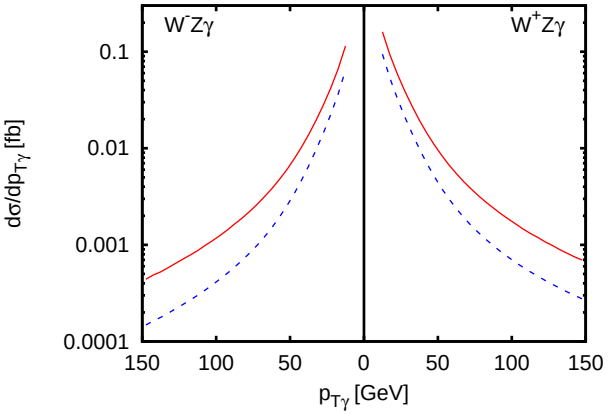


Individual contributions $W^{-}Z\gamma$

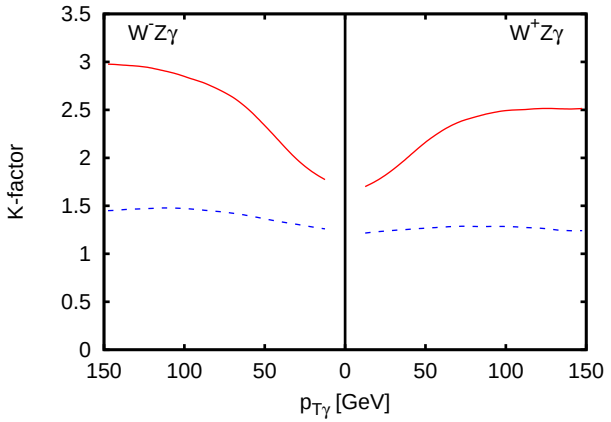


Transverse momentum of the photon

Total cross section NLO/LO



Differential K-factor without/with jet veto



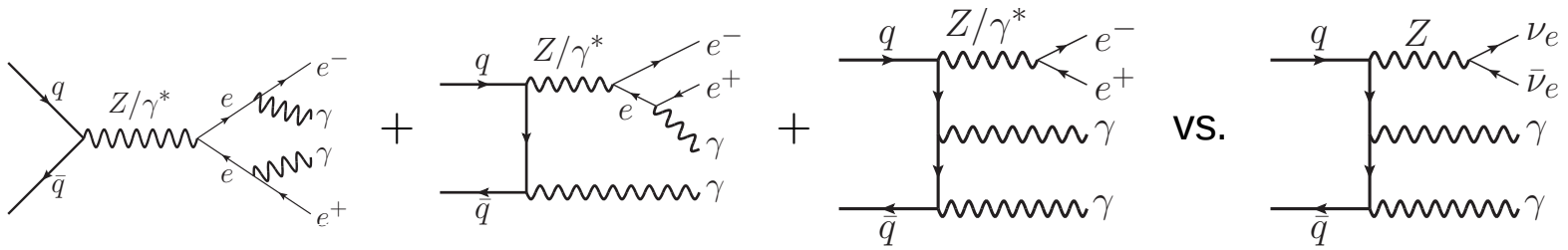
$\Rightarrow$ Sizable K-factor $\sim$ 1.9, strongly dependent on phase-space region

$\Rightarrow$ Fully differential NLO Monte Carlo necessary

$Z\gamma\gamma$

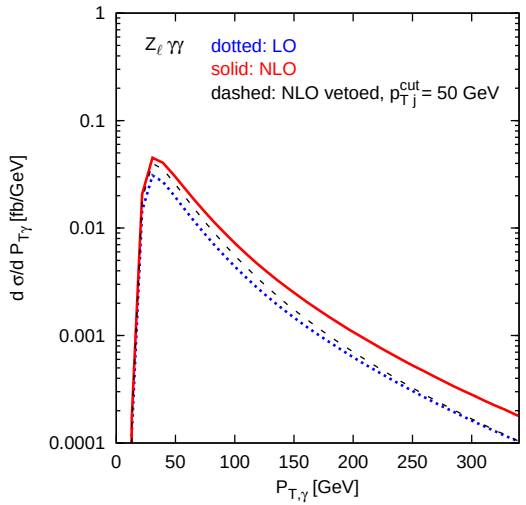
Background to SUSY-GMSB models: $\chi_1^0 \to \gamma\tilde{G}$

- signature: 2 photons plus missing E_T
- irreducible SM background: $pp \to \nu\bar{\nu}\gamma\gamma$
- Extrapolation from $pp \to \ell^+\ell^-\gamma\gamma$ possible?

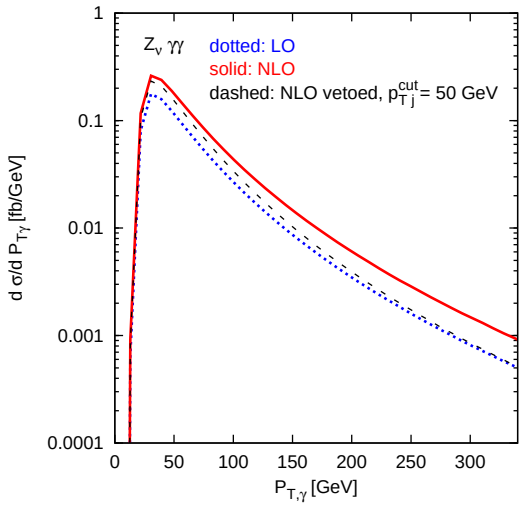


$\Rightarrow$ Cut $m_Z - 2\Gamma_Z < m_{\ell\ell} < m_Z + 2\Gamma_Z$

$pp \to \ell^+\ell^-\gamma\gamma$



$pp \to \nu\bar{\nu}\gamma\gamma$



- $\Rightarrow$ excellent agreement (up to global normalization factor)
- not spoiled by NLO QCD corrections

Diboson plus jet production

[New in VBFNLO v2.5]

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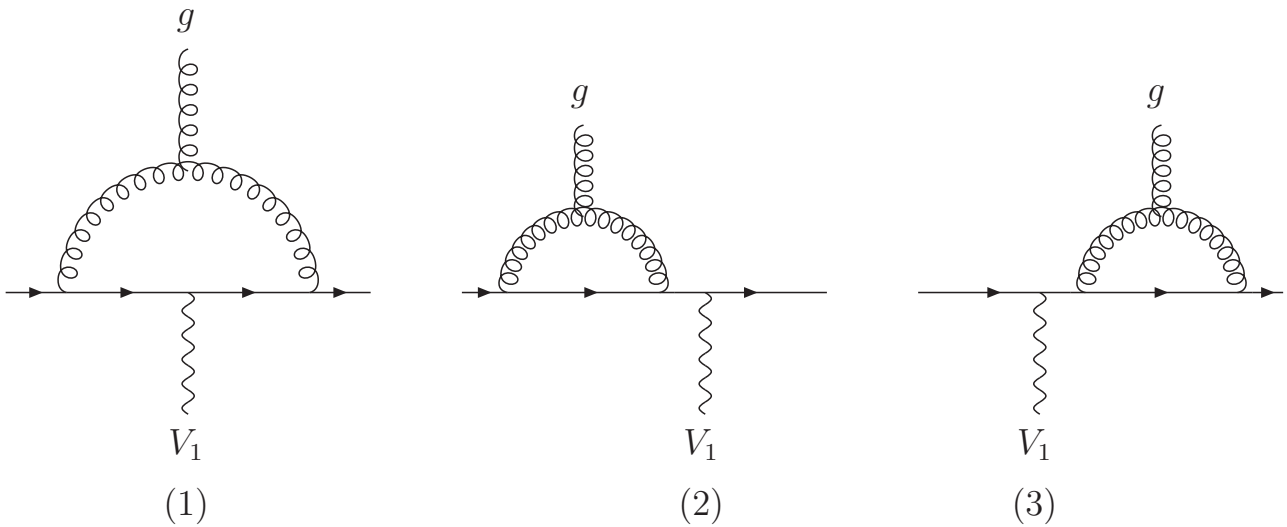
7. $pp \to V\,V\,V$	SUSY trilepton

Processes:

- $(W^{\pm}W^{\mp}j)$ [Dittmaier, Kallweit, Uwer; Campbell, Ellis, Zanderighi]
- $W^{\pm}Zj$ [Campanario, Englert, Kallweit, Spannowsky, Zeppenfeld]
- $W^{\pm}\gamma j$ [Campanario, Englert, Spannowsky, Zeppenfeld]
- $(\gamma\gamma j)$ [Del Duca, Maltoni, Nagy, Trocsanyi]

Diboson plus jet production

- Sizable cross section (1.3 pb for $W^+\gamma j$ at NLO)
- Measurement of anomalous WWZ, $WW\gamma$ coupling
  Dependence of $pp \to WZ\,/W\gamma$ altered by additional jet?
- leptonic decays of W included
- non-Abelian contribution to virtual corrections



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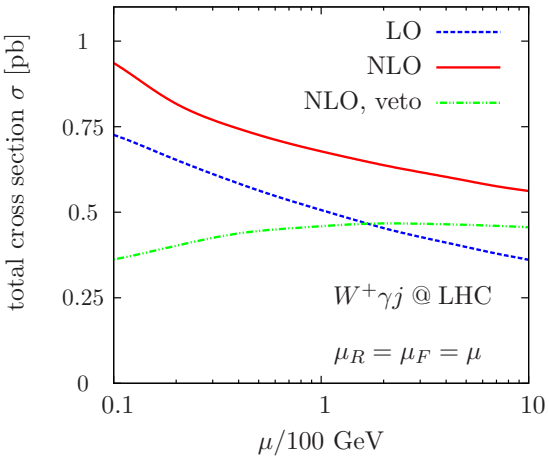
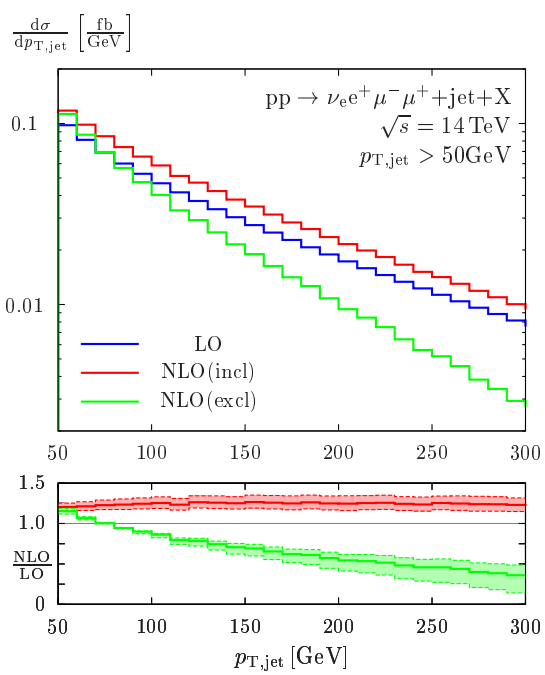
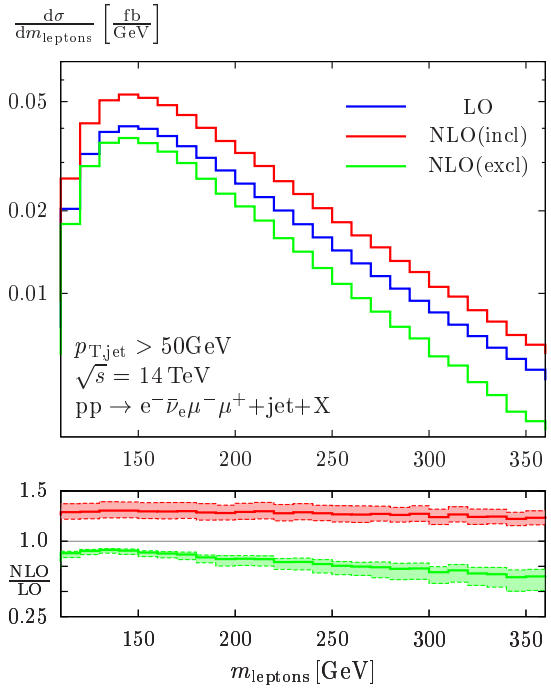
Scale dependence of $W^+\gamma j$



Distributions for WZj





BSM physics

- Anomalous Higgs couplings
  - VBF-Higgs production
- Kaluza-Klein models
  - VBF-diboson production
  - triboson: *WWW*, *WWZ*, *WZZ*
- Three-Site Higgsless model
  - triboson: *WWW*, *WWZ*, *WZZ*
- Anomalous triple and quartic gauge couplings
  - diboson
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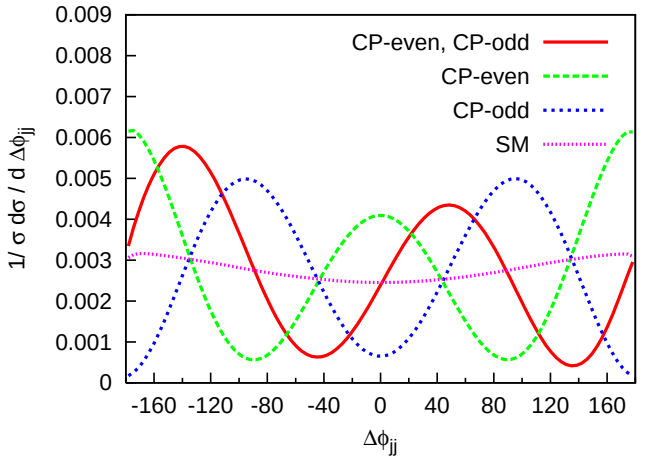

[Hankele, Klämke, Zeppenfeld]

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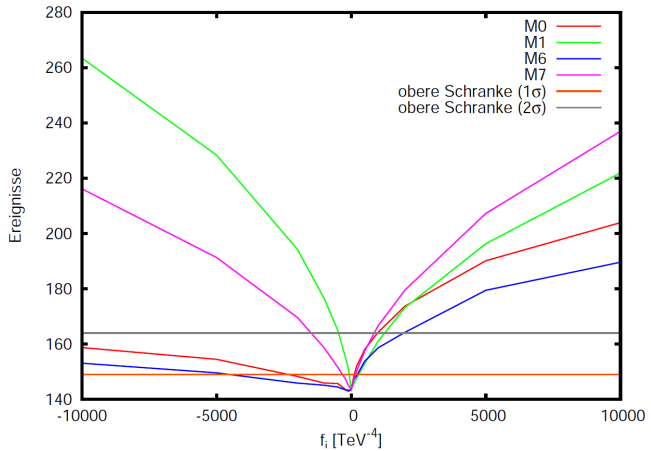

[Feigl, Zeppenfeld]

Conclusions

VBFNLO is a flexible parton-level Monte Carlo for processes with electro-weak bosons

New version out soon including:

- new processes:
  - VBF-Higgs production plus photon
  - VBF photon production
  - Diboson plus jet production: $W^{\pm}Zj$, $W^{\pm}\gamma j$
  - Triboson production: ZZZ, $W^{\pm}W^{\mp}\gamma$, $ZZ\gamma$, $W^{\pm}Z\gamma$, $W^{\pm}\gamma\gamma$, $Z\gamma\gamma$, $\gamma\gamma\gamma$
- new features:
  - EW and SUSY corrections to VBF-Higgs
  - BSM physics: Higgsless Models and anomalous couplings for triboson production

Code available at

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

VBFNLO is collaborative effort:

K. Arnold, M. Brieg, G. Bozzi, 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, M. Rauch, H. Rzehak, F. Schissler, M. Spannowsky, M. Worek, D. Zeppenfeld

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