QCD CORRECTIONS IN VBFNLO

Dieter Zeppenfeld
Karlsruhe Institute of Technology

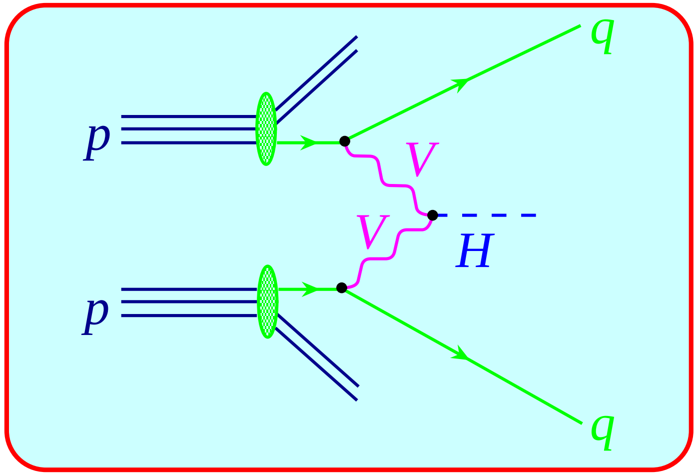
SFB TR9

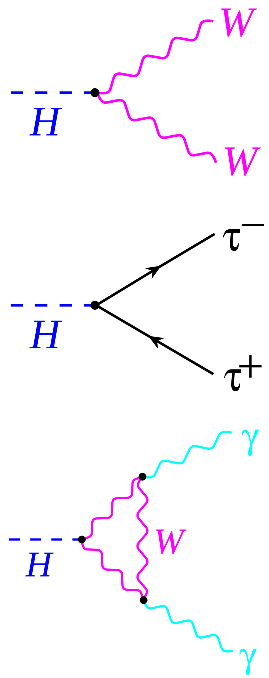
Bundesministerium
für Bildung
und Forschung

LoopFest XI, University of Pittsburgh, May 10-12, 2012

- Vector Boson Fusion
- NLO QCD corrections to VV scattering
- Overview of other NLO QCD processes in VBFNLO
- $W\gamma j$ and $W\gamma\gamma j$ production
- Conclusions

Vector Boson Fusion





$m_H > 120$ GeV

$m_H < 140$ GeV

$m_H < 150$ GeV

[Eboli, Hagiwara, Kauer, Plehn, Rainwater, D.Z. . . .]

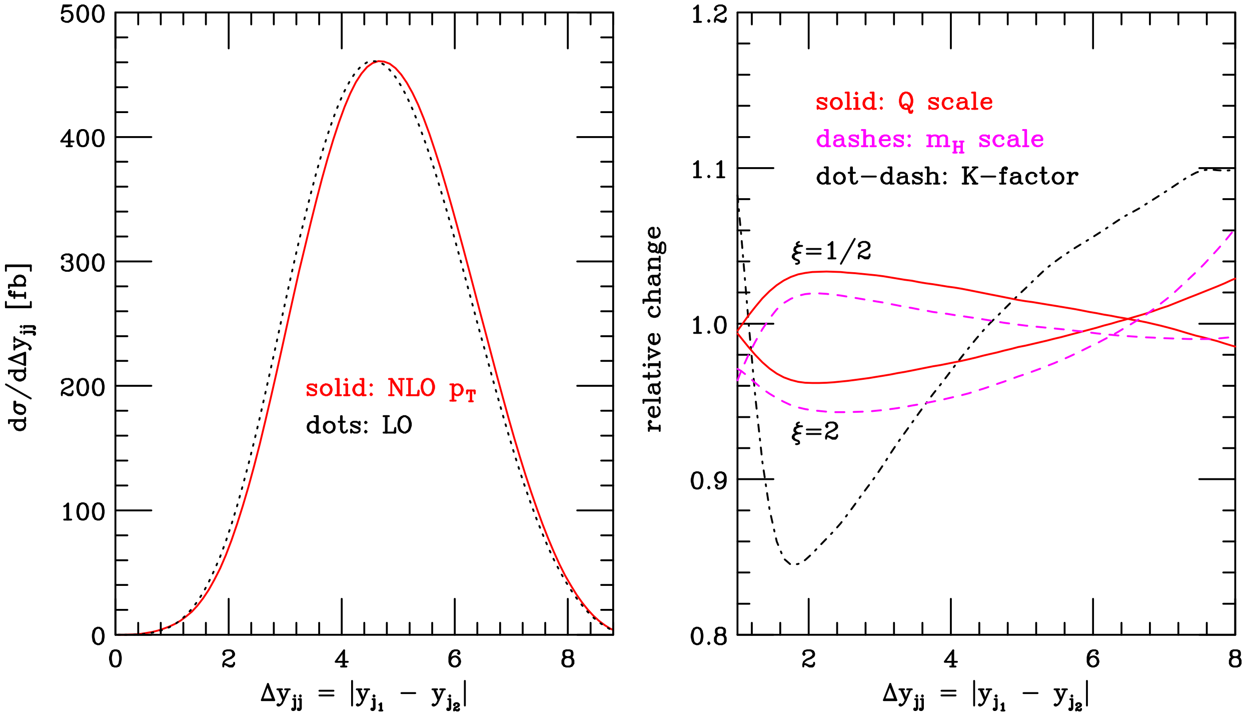
$H \to \gamma\gamma$ in VBF provides significant contribution to CMS Higgs signal at 125 GeV

Most measurements can eventually be performed at the LHC with statistical accuracies on the measured cross sections times decay branching ratios, $\sigma \times$ BR, of order 10%.

Would like theory errors below 5% $\Longrightarrow$ Need NLO corrections

NLO QCD corrections to VBF

- Small QCD corrections of $\mathcal{O}(10\%)$
- Tiny scale dependence at NLO
  - $\pm 5\%$ for distributions
  - $< 2\%$ for σ_{total}
- K-factor is phase space dependent
- QCD corrections under excellent control
  confirmed by NNLO corrections to inclusive VBF cross section
  Bolzoni, Maltoni, Moch, Zaro arXiv:1003.4451
- ✗ Need electroweak corrections for 5% uncertainty
  Ciccolini, Denner, Dittmaier, 0710.4749
  Figy, Palmer, Weiglein arXiv:1012.4789



$m_H = 120$ GeV, typical VBF cuts

NLO corrections to VBF processes available in VBFNLO

Parton level Monte Carlo programs for various NLO calculations, including

- QCD corrections for Higgs production via VBF

  Figy, Oleari, DZ

  Now includes electroweak and SUSY corrections to VBF Higgs production

  Figy,Palmer,Weiglein

- QCD corrections to Higgs plus 3 jet production in VBF

  Figy,Hankele, DZ

- QCD corrections to VBF W and Z production ($qq \to qqV$)

  Oleari, DZ

- QCD corrections to weak boson scattering processes ($qq \to qqVV$)

  Jäger, Oleari, DZ

Limitations of the $qq \to qqH$ picture

At $m_H >$ few hundred GeV (for say $\Gamma_H / m_H > 0.1$) we need to take interference with continuum electroweak into account

Implication:

- Consider full processes $qq \to qqVV$ or $qq \to qq\bar{f}_1 f_2 \bar{f}_3 f_4$
- s-channel Higgs exchange graph with inverse propagator

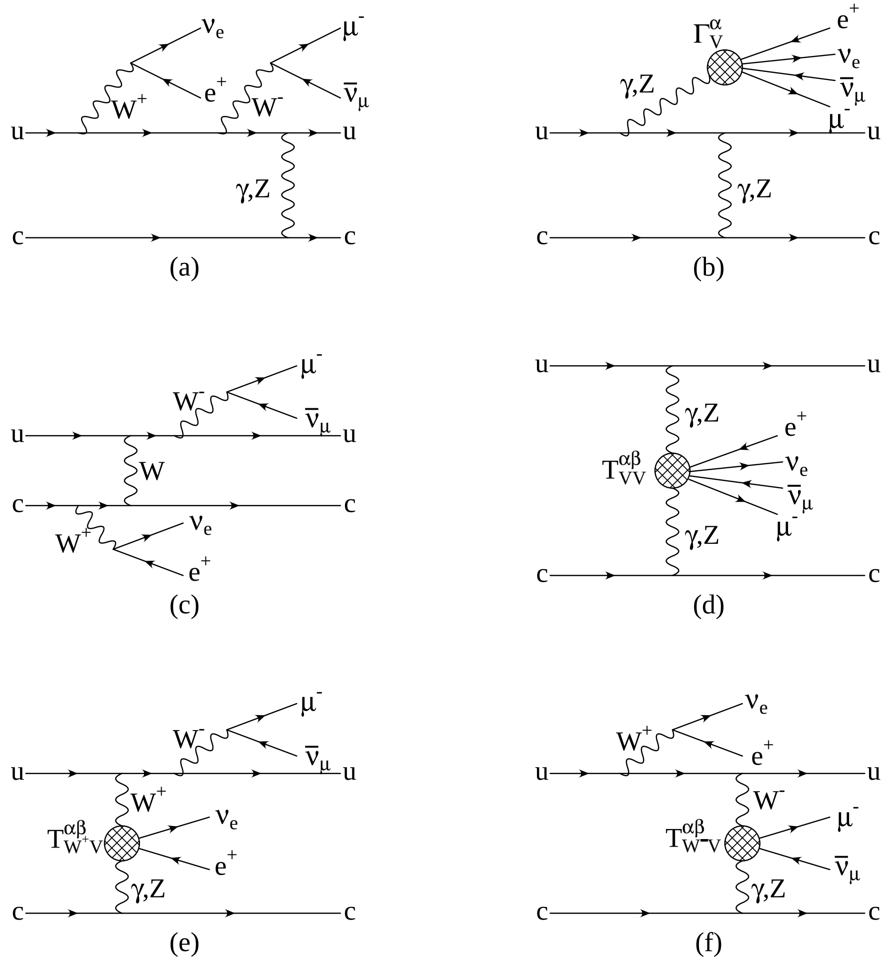
$$\Delta_H(s) = s - s_H = s - m_H^2 + i m_H \Gamma_H$$

is just one contribution.

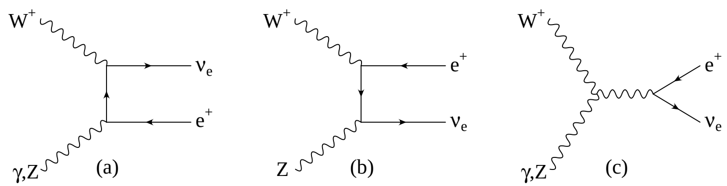
Note: m_H and Γ_H should be treated as free parameters for heavy Higgs
(Γ_H should not necessarily be calculated in SM because EW precision tests give $m_H < 152$ GeV: for larger m_H there must be BSM effects which should also affect the relation between m_H and Γ_H as well as HVV couplings)

Weak boson scattering: $qq \to qqWW$, $qqZZ$, $qqWZ$ at NLO

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



Use modular structure, e.g. leptonic tensor

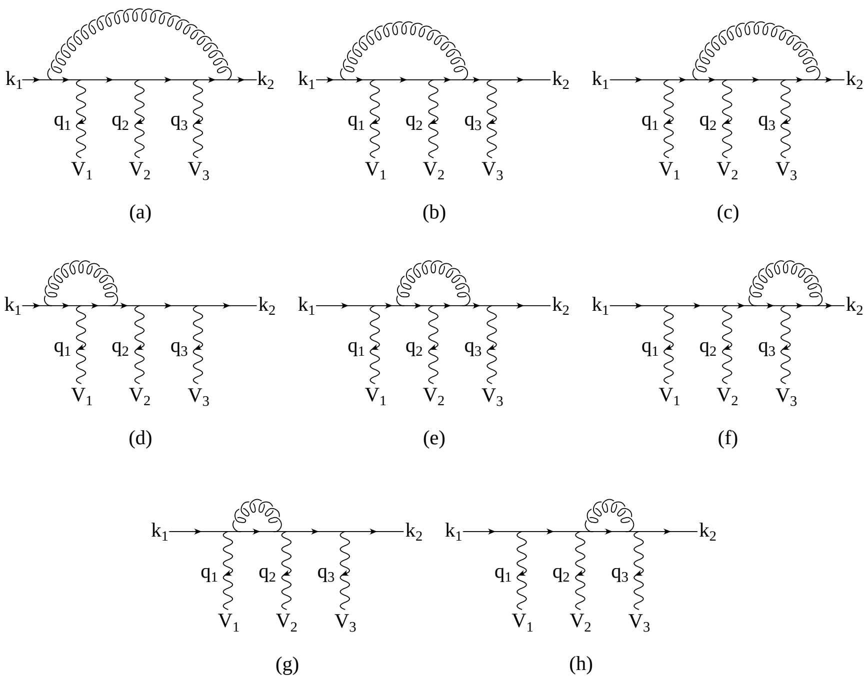


Calculate once, reuse in different processes

Speedup factor $\approx$ 70 compared to MadGraph for real emission corrections

Most challenging for virtual: pentagon corrections

Virtual corrections involve up to pentagons



The external vector bosons correspond to $V \to l_1 \bar{l}_2$ decay currents or quark currents

The sum of all QCD corrections to a single quark line is simple

$$\mathcal{M}_V^{(i)} = \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^{\epsilon} \Gamma(1+\epsilon) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}}\right] + \widetilde{\mathcal{M}}^{(i)}_{V_1V_2V_3,\tau}(q_1,q_2,q_3) + \mathcal{O}(\epsilon)$$

- Divergent pieces sum to Born amplitude: canceled via Catani Seymour algorithm
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Pentagon tensor reduction with Denner-Dittmaier is stable at 0.1% level

Phenomenology

Study LHC cross sections within typical VBF cuts

- Identify two or more jets with k_T-algorithm ($D = 0.8$)

$$p_{Tj} \geq 20\ \text{GeV}\,, \qquad |y_j| \leq 4.5$$

- Identify two highest p_T jets as tagging jets with wide rapidity separation and large dijet invariant mass

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad M_{jj} > 600\ \text{GeV}$$

- Charged decay leptons ($\ell = e,\ \mu$) of W and/or Z must satisfy

$$p_{T\ell} \geq 20\ \text{GeV}\,, \qquad |\eta_\ell| \leq 2.5\,, \qquad \triangle R_{j\ell} \geq 0.4\,,$$
$$m_{\ell\ell} \geq 15\ \text{GeV}\,, \qquad \triangle R_{\ell\ell} \geq 0.2$$

and leptons must lie between the tagging jets

$$y_{j,min} < \eta_\ell < y_{j,max}$$

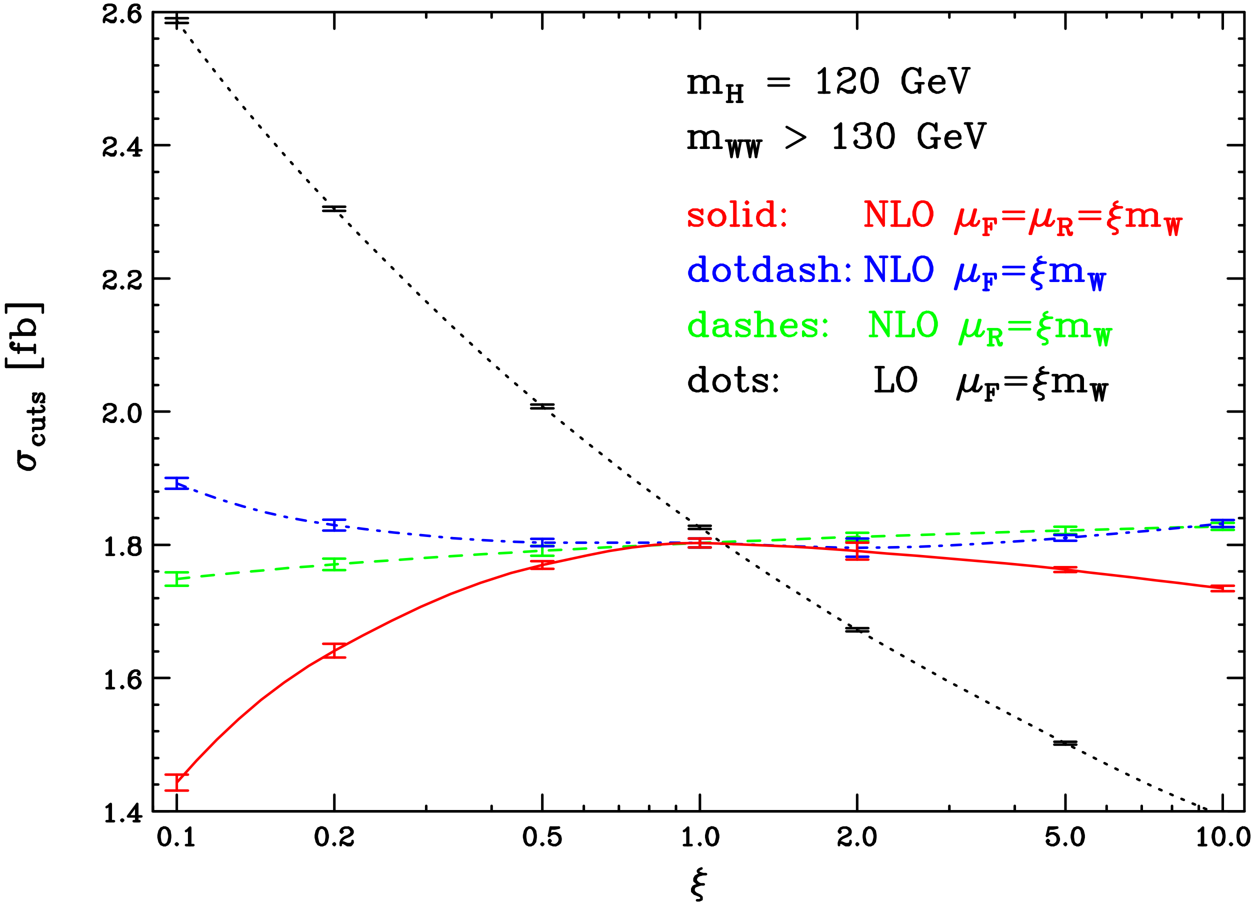
For scale dependence studies we have considered

$\mu = \xi\ m_V$ fixed scale $\qquad \mu = \xi\ Q_i$ weak boson virtuality : $Q_i^2 = 2k_{q_1} \cdot k_{q_2}$

WW production: $pp \to jje^+\nu_e\mu^-\bar{\nu}_\mu X$ @ LHC

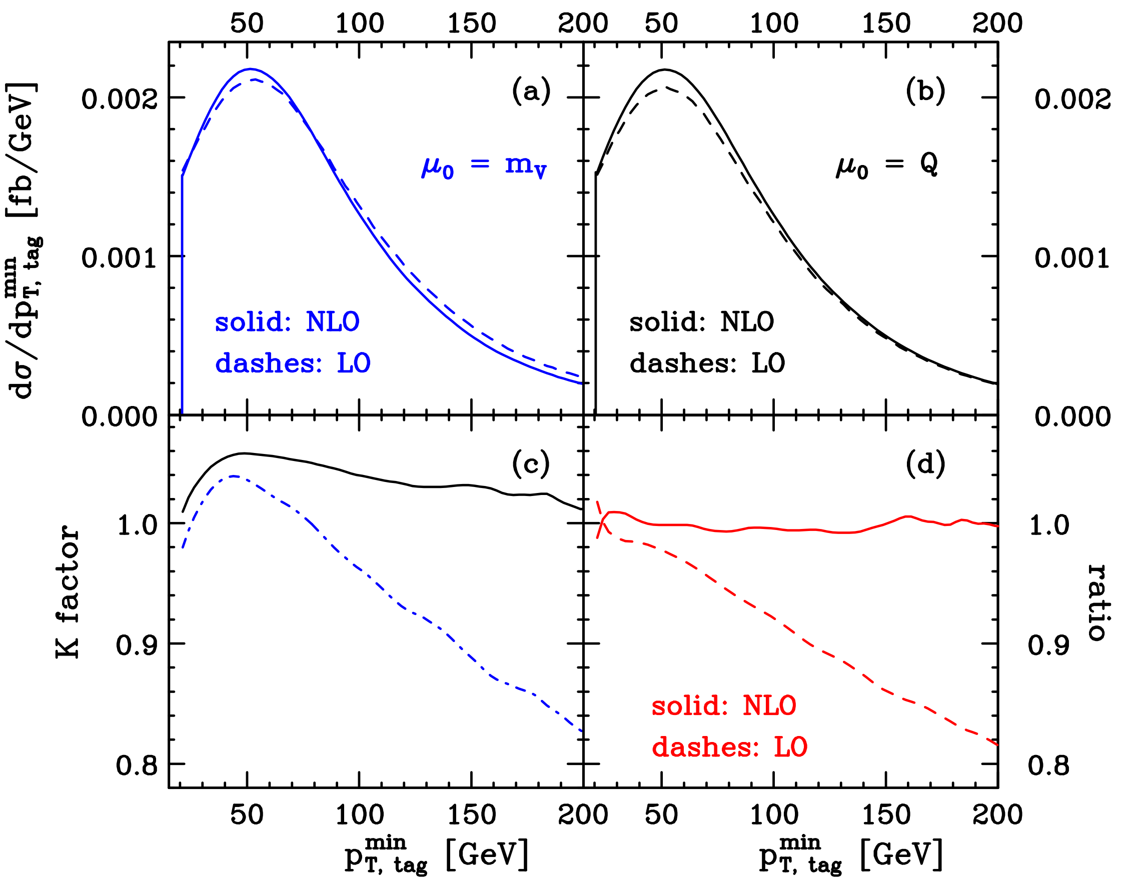
Stabilization of scale dependence at NLO

Jäger, Oleari, DZ hep-ph/0603177



WZ production in VBF, $WZ \to e^+ \nu_e \mu^+ \mu^-$

Transverse momentum distribution of the softer tagging jet

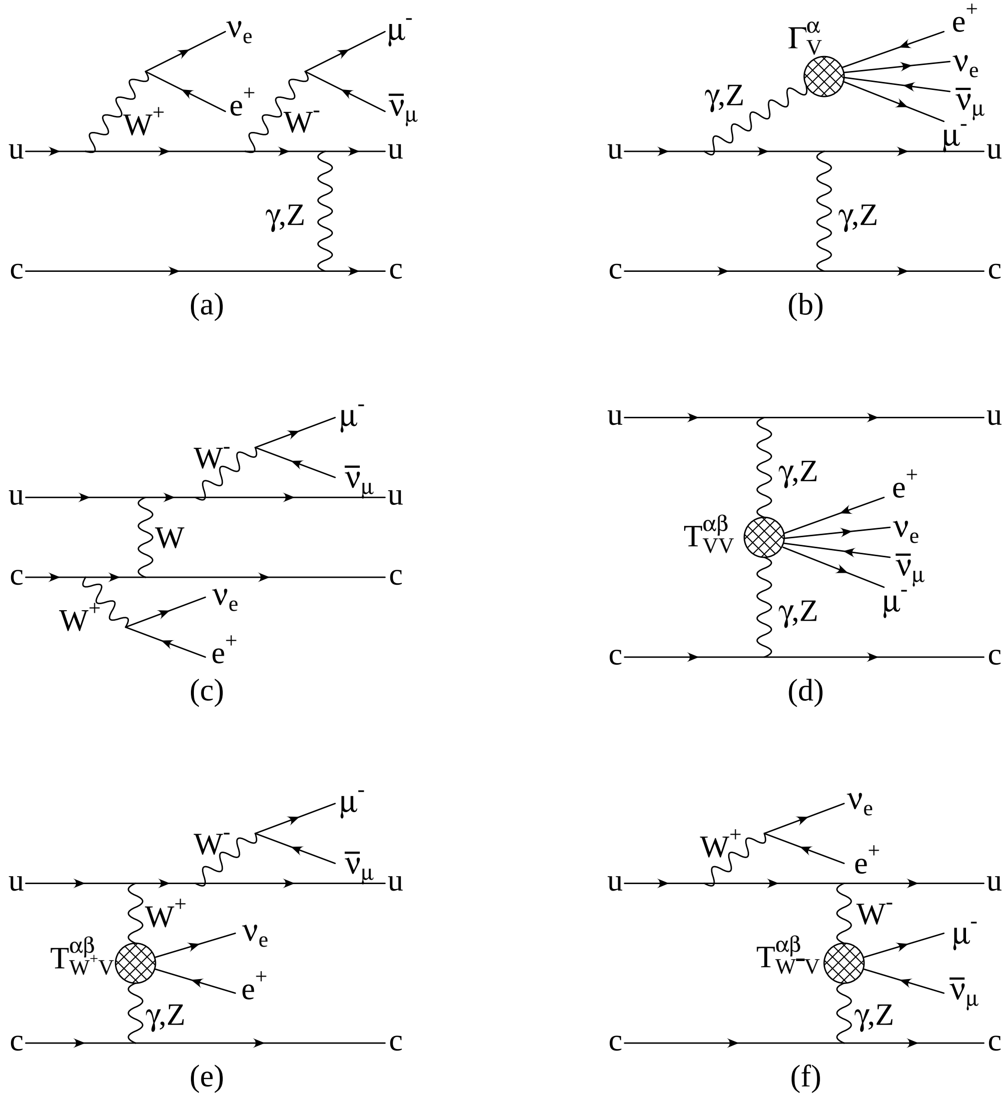


- Shape comparison LO vs. NLO depends on scale
- Scale choice $\mu = Q$ produces approximately constant K-factor
- Ratio of NLO curves for different scales is unity to better than 2%: scale choice matters very little at NLO

Use $\mu_F = Q$ at LO to best approximate the NLO results

$qq \to qqVV$: 3 weak bosons on a quark line

- NLO corrections to $qq \to qqVV$ contain all loops with a virtual gluon attached to a quark line with one, two or three weak bosons
- Crossing and replacing one quark line by a lepton line yields $q\bar{q} \to VVV$ production processes with leptonic decays of the weak bosons
- Recycle virtual contributions from NLO corrections to VBF
- Decompose calculation into modules which can be used in different NLO calculations



Extending VBFNLO: VVV and VVj Production at NLO QCD

Additional processes implemented in 2008 release of VBFNLO:

- Triple weak boson production: $VVV = W^{\pm}W^{\mp}W^{\pm}$, $W^{+}W^{-}Z$ and $W^{\pm}ZZ$ with leptonic decay of the weak bosons and full $H \rightarrow WW$ and $H \rightarrow ZZ$ contributions
  Work in collaboration with V. Hankele, S. Prestel, C. Oleari and F. Campanario

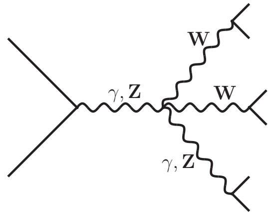
New processes which were made available in 2011 release:

- $W^{+}W^{-}\gamma$, $ZZ\gamma$ $WZ\gamma$, $W\gamma\gamma$ production with leptonic decay of weak bosons
  Work in collaboration with G. Bozzi, F. Campanario, M. Rauch, H. Rzehak
- $W^{\pm}\gamma j$ and WZj production (with W, Z leptonic decay and final state photon radiation)
  Work with C.Englert, F. Campanario, S. Kallweit, M. Spannowsky
- $H\gamma jj$ production in VBF
  Work in collaboration with K. Arnold, B. Jäger, T. Figy
- BSM effects like anomalous couplings and heavy vector resonances

Code is available at http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb/

VVV Production: Motivation

- Standard Model background for SUSY processes with multi-lepton + $\not{p}_T$ signature
- Possibility to obtain information about quartic electroweak couplings.



- QCD corrections to $pp \rightarrow$ VVV + X on experimentalist's wishlist:

  [The QCD, EW, and Higgs Working Group: hep-ph/0604120]

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

Input variables for LHC phenomenology

- **PDFs**: CTEQ6L1 at LO and CTEQ6M, $\alpha_S(m_Z) = 0.118$ at NLO.

- **Cuts and Masses**:

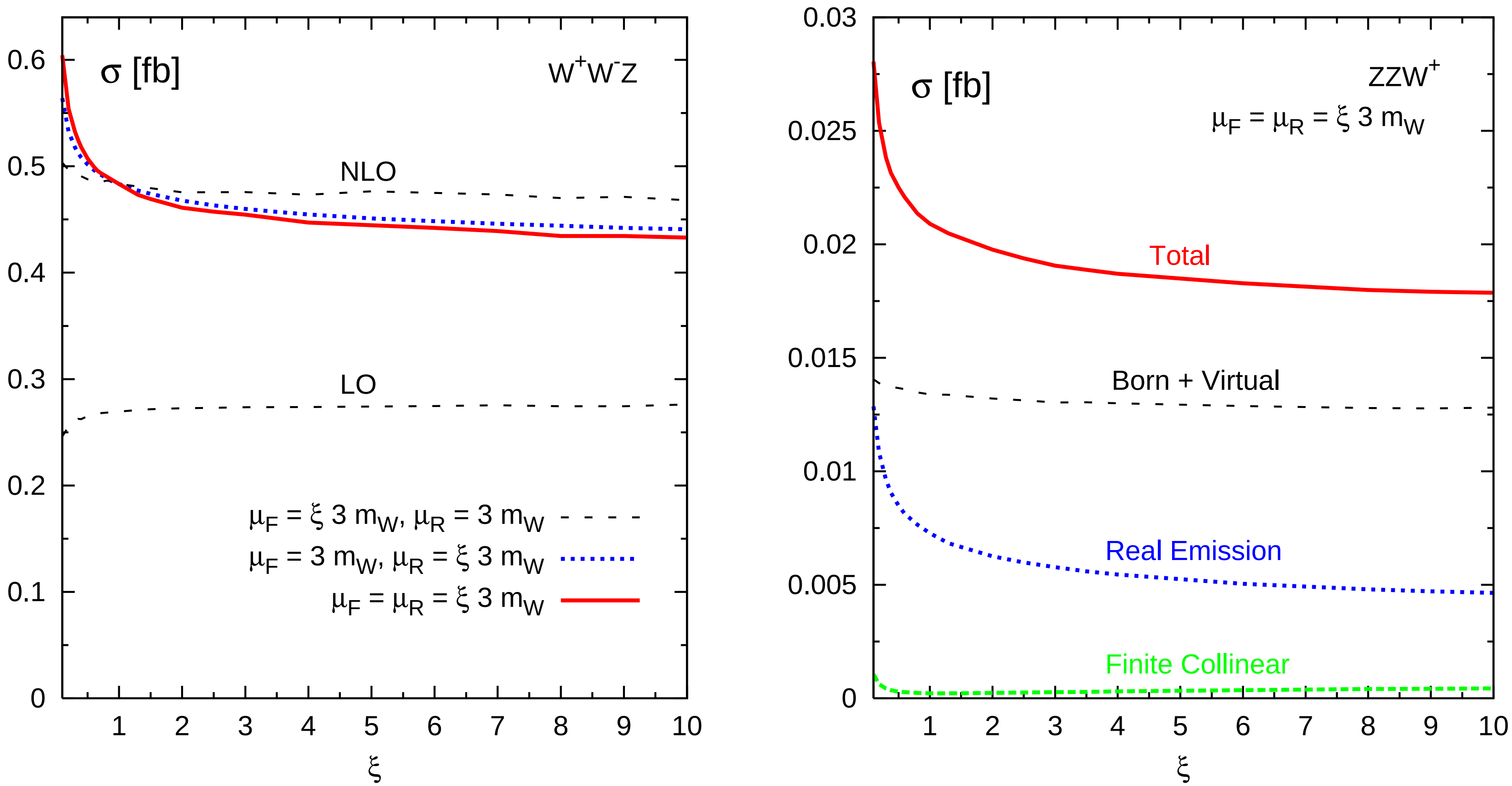
$$p_{T_\ell} > 10\ \text{GeV}, \qquad |\eta_\ell| < 2.5, \qquad m_{\ell^+\ell^-} > 15\ \text{GeV}, \qquad m_H = 120\ \text{GeV}.$$

- **Renormalization- and Factorization Scale**: $\mu_F = \mu_R = 3\, m_W$.

Following results are for electrons and/or muons in the final state:

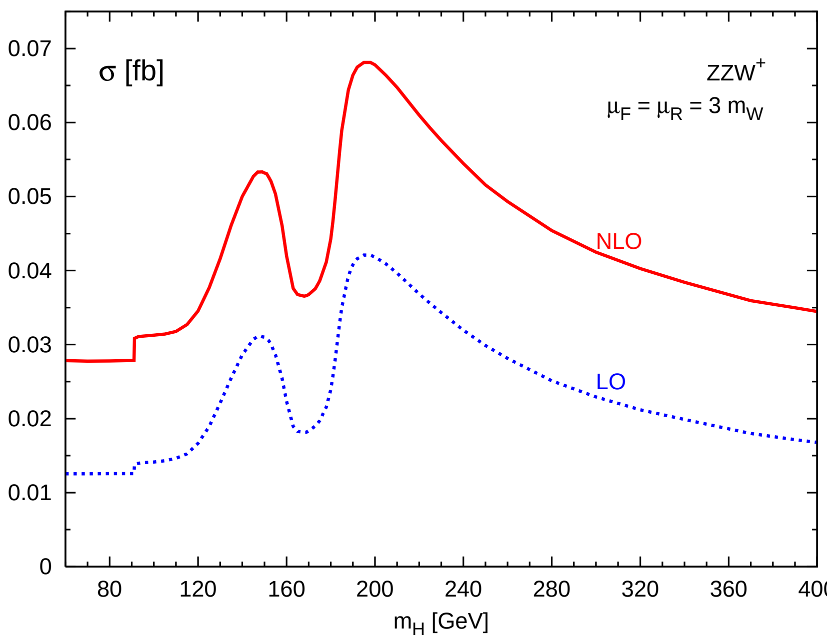
$\Longrightarrow$ Combinatorial factor of 8/4 for the $W^+W^-Z/ZZW^\pm$ production compared to three different lepton families in the final state.

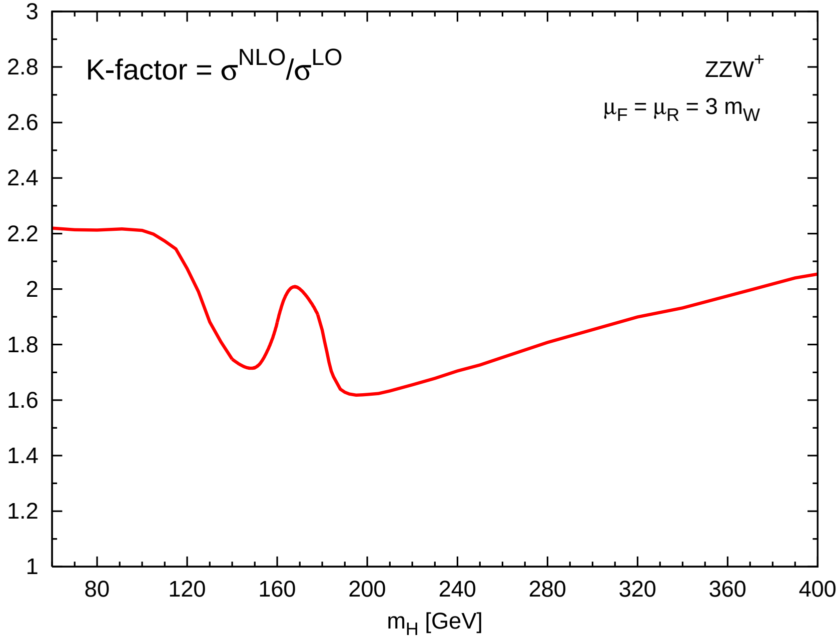
Scale Dependence

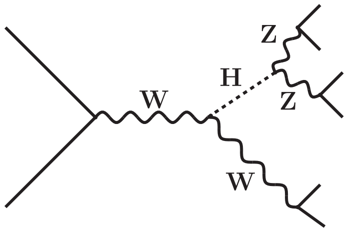


- At LO only small μ_F-dependence, no $\alpha_s(\mu_R)$.
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$.
- Real emission contribution drives overall scale dependence at NLO.

Higgs mass dependence

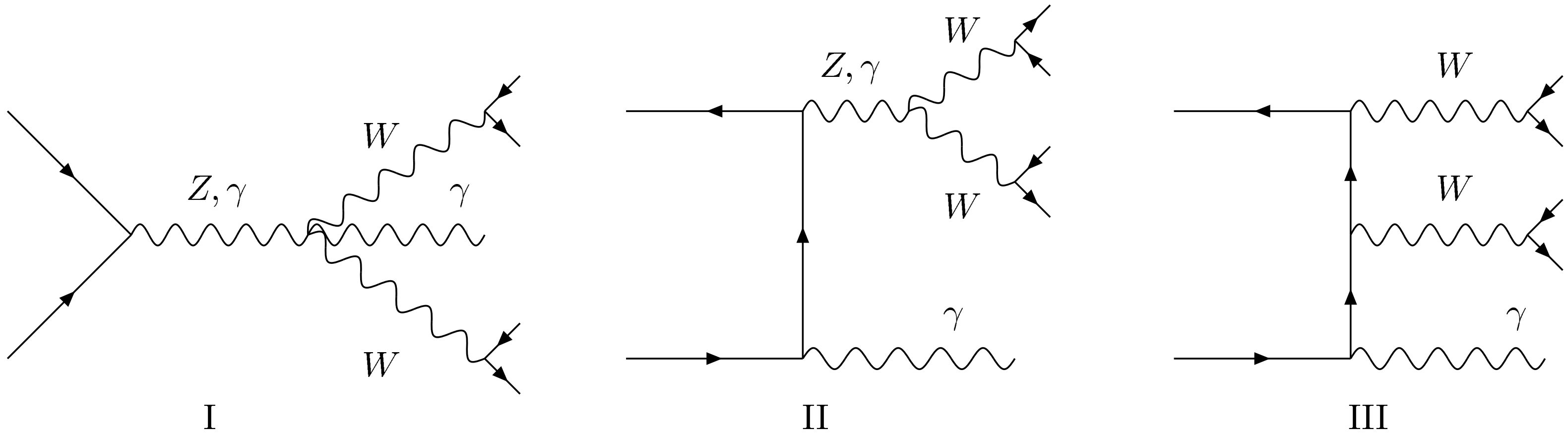






- Cross section reflects behavior of $BR(H \to ZZ)$
- K-factor is reduced by Higgs contribution.
  K-factor for $pp \to ZH$ production is about K = 1.3
  $\Longrightarrow$ Different K-factor for resonance production

Extension to final state photons: $W^+W^-\gamma$ and more



New elements of calculation:

- Different infrared divergence structure of individual loop integrals but same final virtual expressions in terms of finite parts of C_{ij}, D_{ij}, and E_{ij} functions
- Photon isolation from jets for real emission contributions: use Frixione isolation

$$\Sigma_i E_{T_i} \theta(\delta - R_{i\gamma}) \leq p_{T_\gamma} \frac{1-\cos\delta}{1-\cos\delta_0} \qquad (\text{for all} \quad \delta \leq \delta_0)$$

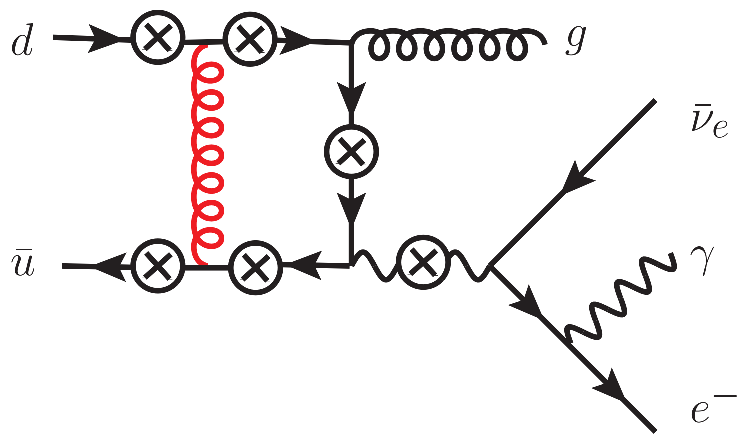
- Final state photon radiation becomes important: adapt phase space to this

NLO QCD Corrections to $W\gamma j$ Production

- Provide NLO QCD corrections including leptonic W decay, e.g.

$$pp \to e^+ \nu_e \gamma j\,, \qquad pp \to e^- \bar{\nu}_e \gamma j$$

- Sizable cross section at LHC (1.2 pb) and Tevatron (15 fb) for $p_{Tj}, p_{T\gamma} > 50$ GeV and separation cuts (later)
- Measurement of anomalous $WW\gamma$ coupling: veto on jets in $W\gamma$ events requires good knowledge of cross section and distributions: want NLO
- Photon isolation à la Frixione probed at NLO level



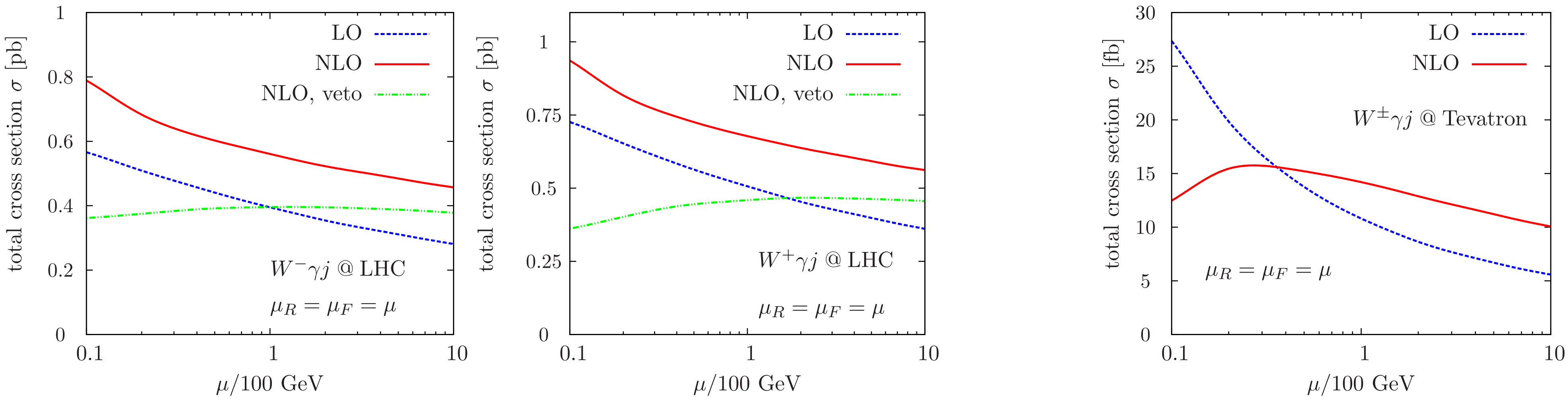
- Initial and final state photon radiation. Final radiation from lepton is important
- Virtual corrections up to pentagons
- External gluon already at tree level $\Longrightarrow$ *nonabelian* boxes with three gluon vertex
- Larger number of subtraction terms

Scale dependence: LHC and Tevatron

Identify lepton, photon and one or more jets with k_T-algorithm ($D = 0.7$)

$p_{Tj,\gamma} \geq 50\,\text{GeV}\,, \quad |y_j| \leq 4.5\,, |\eta_\gamma| \leq 2.5,$ $\qquad p_{Tl} \geq 20\,\text{GeV}\,, \quad |\eta_l| \leq 2.5$ $\qquad R_{l,\gamma}, R_{l,j} > 0.2$

Frixione isolation of photons with $\delta_0 = 1$ Cross sections are for $W \to e\nu_e$ only

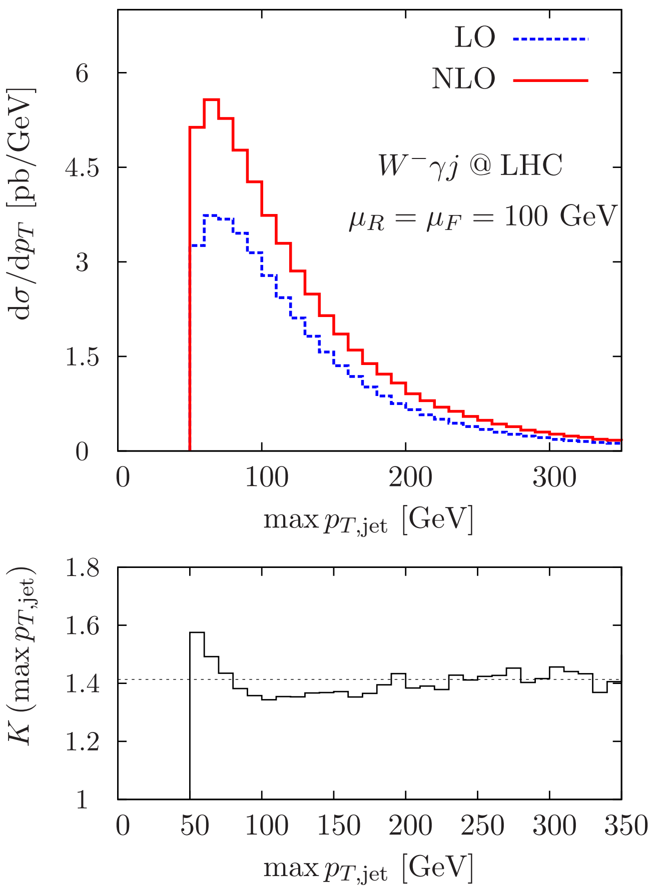


Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm 1} \cdot 100$ GeV: $\pm 11\%$ at LO reduced to $\pm 7\%$ at NLO

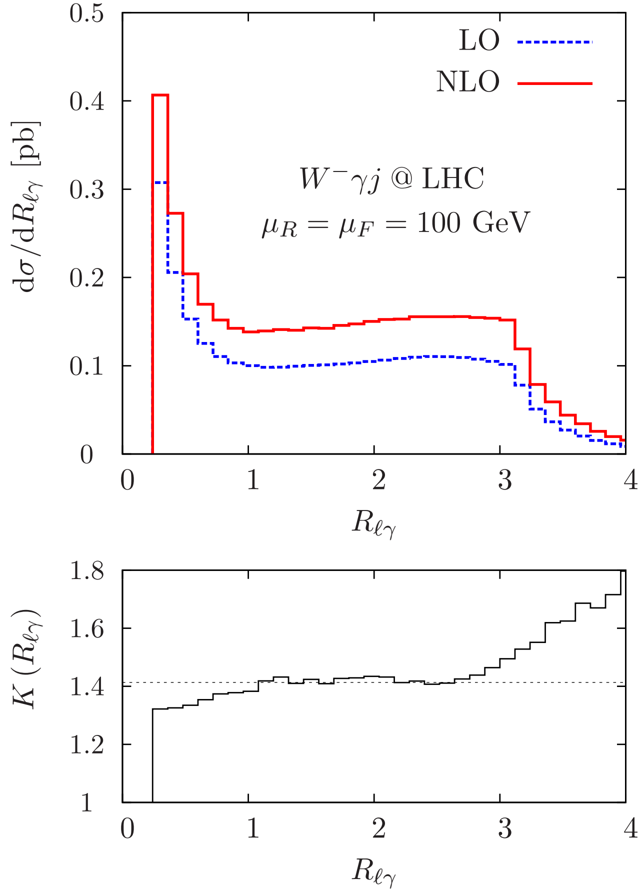
Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV should be taken as accidental and not as a measure of NLO uncertainties

NLO corrections to distributions

p_T of hardest jet



lepton photon separation



- Clear shape changes of distributions when going from LO to NLO
- Average K-factor of 1.4 at LHC is significantly larger than LO scale variation

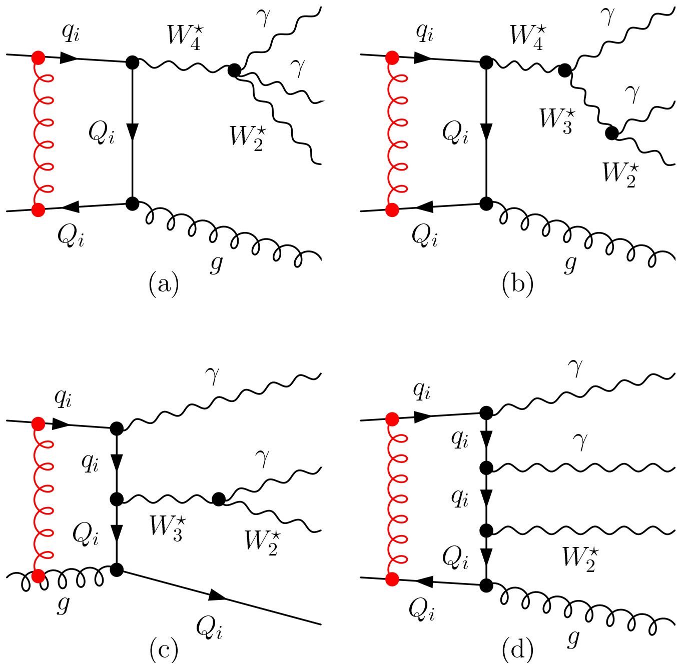
NLO QCD Corrections to $W\gamma\gamma j$ Production

Campanario, Englert, Rauch, DZ arXiv:1106.4009

- Provide NLO QCD corrections including leptonic W decay, e.g.

$$pp \to e^+ \nu_e \gamma\gamma j\,, \qquad pp \to e^- \bar{\nu}_e \gamma\gamma j$$

- LHC14 cross section is about 25 fb for p_{Tj}, $p_{T\gamma}$, $p_{Tl} > 20$ GeV and separation cuts (later)
- Measurement of anomalous $WW\gamma\gamma$ coupling: veto on jets in $W\gamma$ events requires good knowledge of cross section and distributions: want NLO



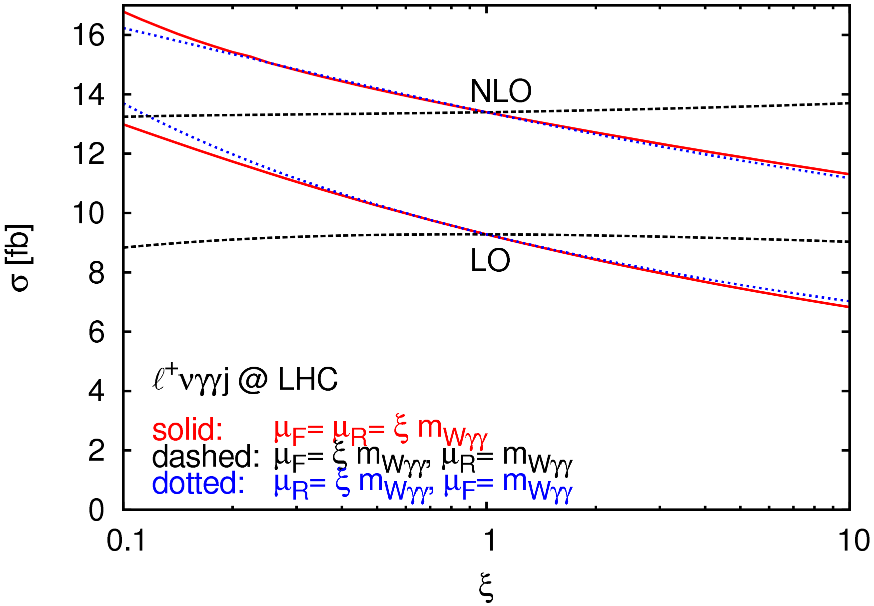
- Initial and final state photon radiation. Final radiation from lepton is important
- Virtual corrections up to hexagons

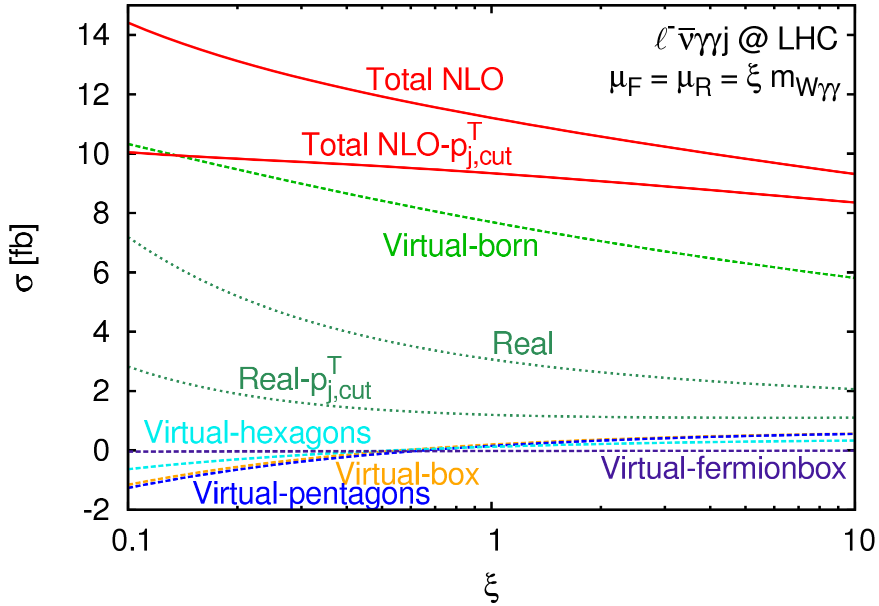
Scale dependence at LHC

Identify lepton, photon and one or more jets with k_T-algorithm ($D = 0.7$)

$p_{Tj,\gamma} \geq 20\,\text{GeV}\,, \quad |y_j| \leq 4.5\,, |\eta_\gamma| \leq 2.5, \qquad p_{Tl} \geq 20\,\text{GeV}\,, \quad |\eta_l| \leq 2.5 \qquad R_{l,\gamma}, R_{l,j} > 0.4$

Frixione isolation of photons with $\delta_0 = 0.7$

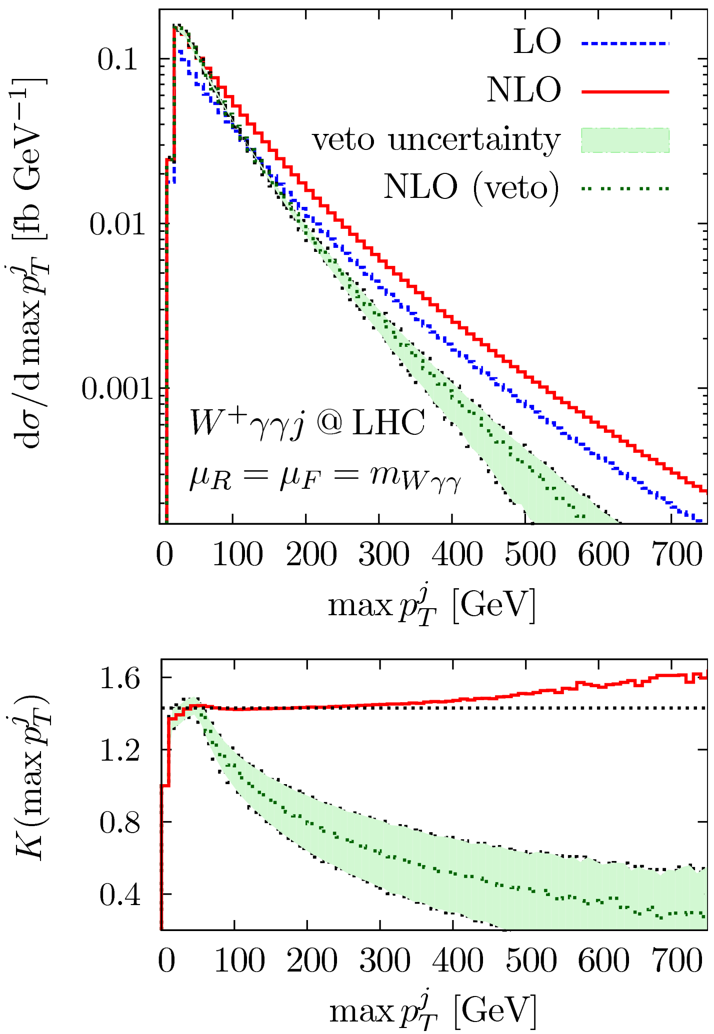




Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm 1} \cdot m_{W\gamma\gamma}$ $\pm 11\%$ at NLO (not much reduced from LO)

Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV

Scale variation with jet veto



Consider p_T of hardest jet

- Jet veto introduces very large scale variations at high p_T
- Small scale dependence in integrated cross section due to accidental cancellation between different phase space regions

Extensions in 2012 update of VBFNLO

Additional NLO QCD corrected processes implemented in 2012 release of VBFNLO:

- $W\gamma\gamma j$ production as first true 2→4 process
- Triple weak boson production is now complete: all $V_1V_2V_3$ production processes for any $V_i = W^{\pm}, Z, \gamma$
- Same sign WW scattering in VBF: W^+W^+jj final states
- Diboson production processes (WZ, $W\gamma$, ZZ, $Z\gamma$ and $\gamma\gamma$) now included.
  WZ and $W\gamma$ production are provided with anomalous WWV couplings
- Anomalous couplings implemented in the VBF production of Vjj final states
- Spin 2 resonance implemented in VBF: test if Higgs has spin 0 or spin 2

Conclusions

- VBFNLO provides NLO QCD corrections to a host of processes, in particular vector boson fusion, VVV production and VVj production
- All off-shell diagrams as well as the Higgs-contributions have been considered.
- VBFNLO also contains hjj production from gluon fusion at LO with full quark and squark mass dependence

  Code of 2011 release is available at
  http://www-itp.particle.uni-karlsruhe.de/∼vbfnloweb
- 2012 updates will include $W\gamma\gamma$ jet production at NLO and WZ and $W\gamma$ production with anomlous triple gauge interactions
- VBFNLO is collaborative effort! Thanks to
  V. Hankele, B. Jäger, M. Worek, S. Palmer, F. Campanario, M. Rauch, C. Oleari, K. Arnold, J. Bellm, G. Bozzi, C. Englert, B. Feigl, T. Figy, J. Frank, M. Kerner, G. Klämke, M. Kubocz, S. Plätzer, S. Prestel, H. Rzehak, F. Schissler, M. Spannowsky