NLO QCD CORRECTIONS TO PROCESSES WITH MULTIPLE ELECTROWEAK BOSONS

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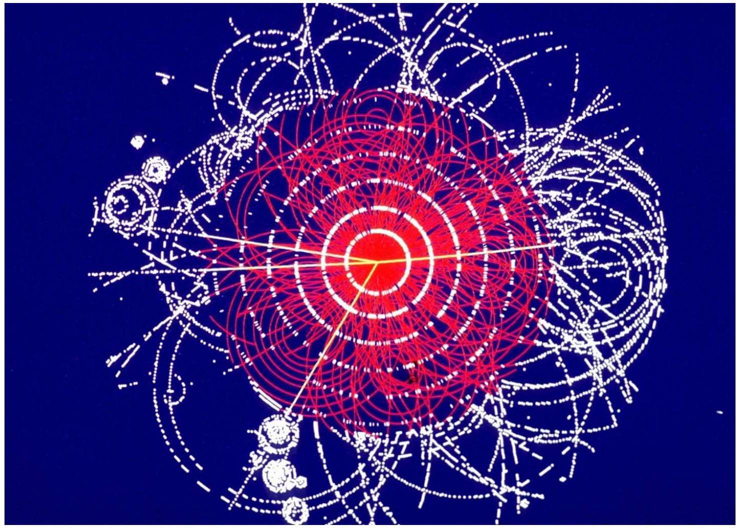
- Introdution: VBFNLO
- NLO for WWW, WWZ and WZZ production
- $WW\gamma$ and $ZZ\gamma$ at NLO
- $W\gamma j$ production at NLO
- Conclusions



Beginnings of VBFNLO: QCD corrections to VBF processes

NLO predictions for vector boson fusion processes at the LHC:

$qq \to qqH$ Han, Valencia, Willenbrock (1992); Figy, Oleari, DZ (2003); Campbell, Ellis, Berger (2004)

- Higgs coupling measurements

$qq \to qqZ$ and $qq \to qqW$ Oleari, DZ: hep-ph/0310156

- $Z \to \tau\tau$ as background for $H \to \tau\tau$
- measure central jet veto acceptance at LHC

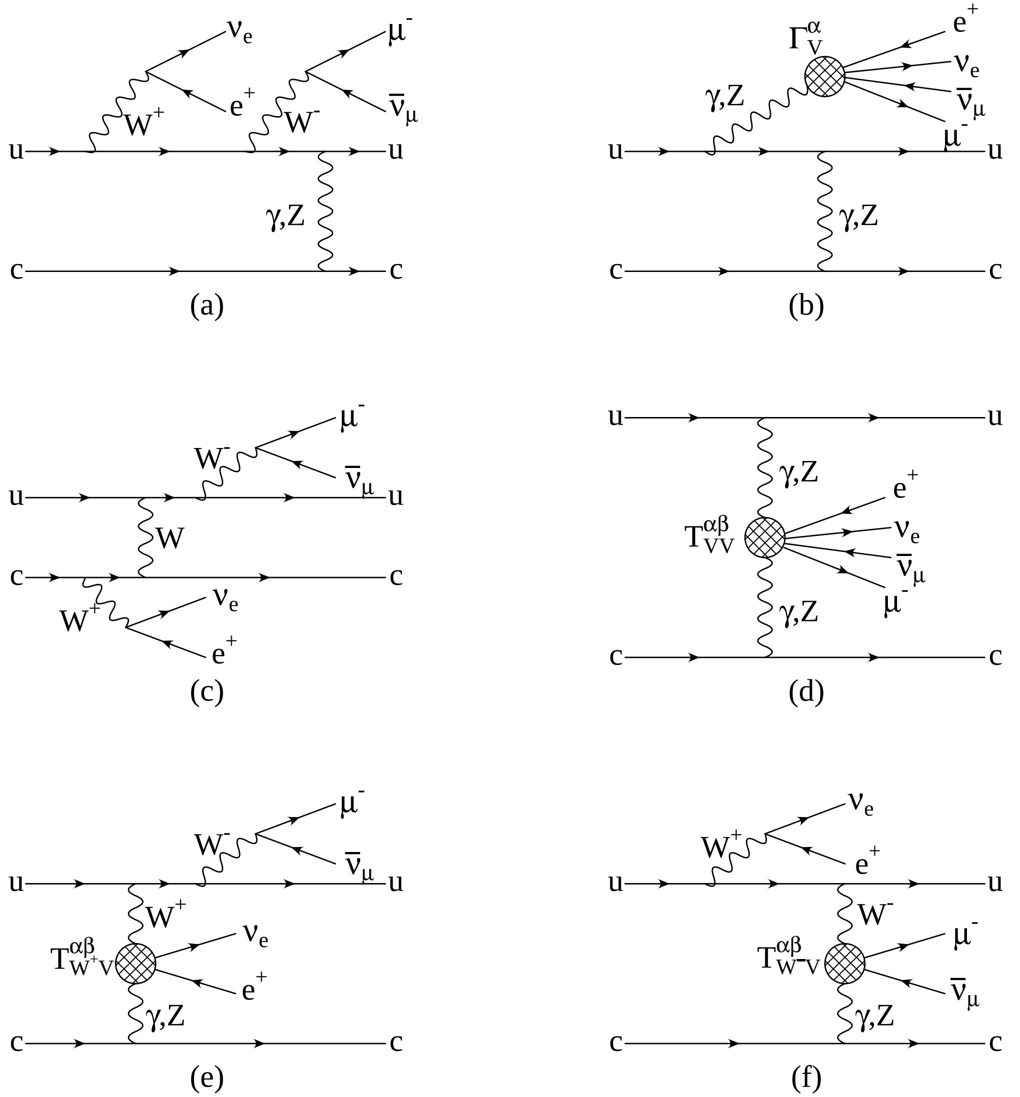
$qq \to qqWW$, $qq \to qqZZ$, $qq \to qqWZ$ Jäger, Oleari, Bozzi, DZ: hep-ph/0603177, hep-ph/0604200, hep-ph/0701105, arXiv:0907.0580

- $qqWW$ is background to $H \to WW$ in VBF
- underlying process is weak boson scattering: $WW \to WW$, $WW \to ZZ$, $WZ \to WZ$ etc.

$\Longrightarrow$ Talk by Barbara Jäger

$qq\to qqVV$: 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

New 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 $H \to WW$ and $H \to ZZ$ contributions
  Work in collaboration with V. Hankele, S. Prestel, C. Oleari and F. Campanario

New processes already available for future releases:

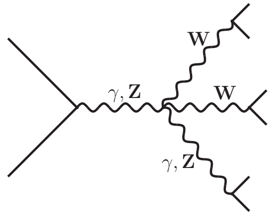
- $W^+W^-\gamma$ and $ZZ\gamma$ production with leptonic decay of weak bosons
  Work in collaboration with G. Bozzi and F. Campanario

- $W^\pm\gamma j$ production (with W leptonic decay and final state photon radiation)
  Work in collaboration with C.Englert, F. Campanario and M. Spannowsky

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.

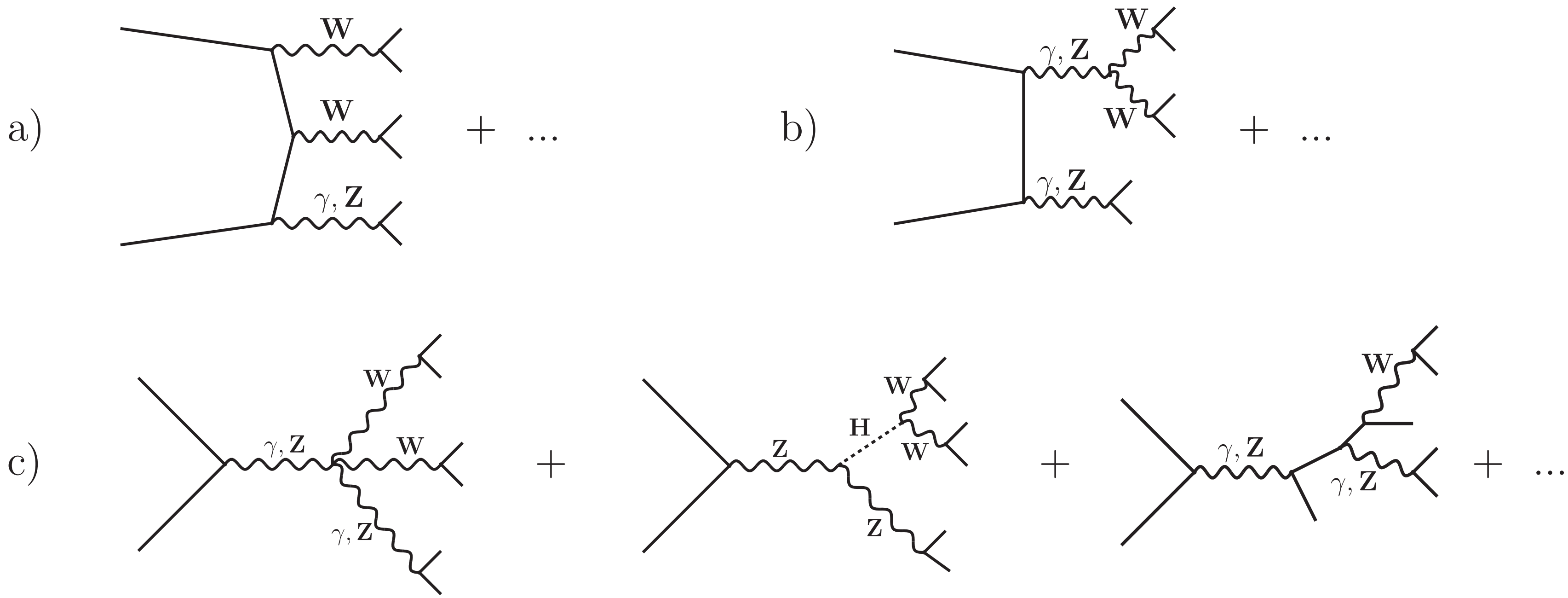


- QCD corrections to $pp \to$ VVV + X on experimentalist's wishlist:

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

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ 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

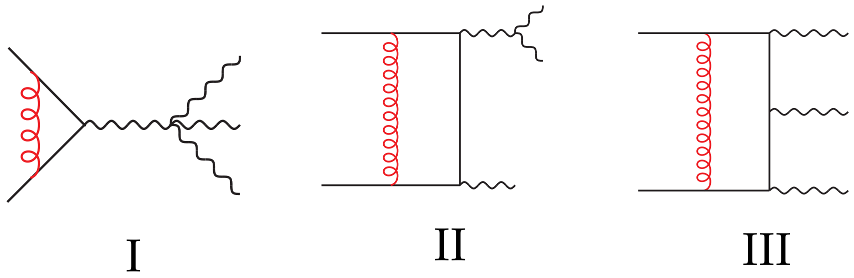
Example: Contributions to WWZ production

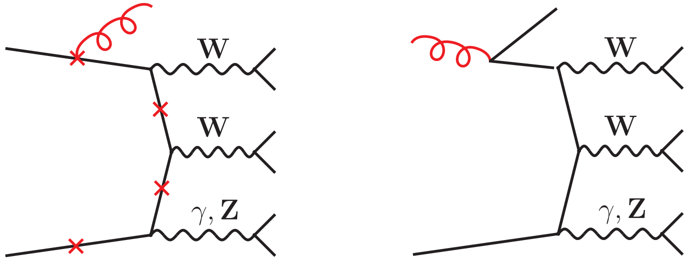


- All resonant and non-resonant matrix elements as well as spin correlations of final state leptons and Higgs contribution included.
- Interference terms due to identical particles in the final state have been neglected.
- All fermion mass effects neglected. ($H\tau\tau$-coupling = 0)

1-loop matrix elements and real emission matrix elements

Three different topologies:



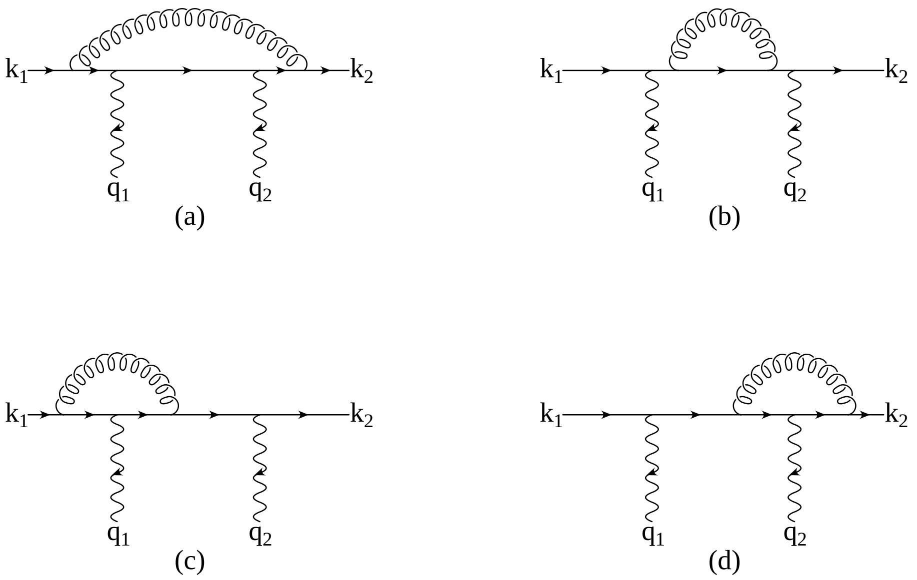


- I Vertex correction proportional to Born matrix element.
- II Maximally 4-point integrals appear.
- III Up to five external legs (Pentagons):
  - Two independent calculations.
  - Numerically stable results with Denner Dittmaier method.

- Two different classes: final state gluon and initial state gluon.
- Each of them consists of several hundred Feynman-Graphs.
- Soft and collinear singularities subtracted with Catani-Seymour presription

Boxline corrections

Virtual corrections for quark line with 2 EW gauge bosons



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

Divergent terms in 4 Feynman graphs combine to multiple of corresponding Born graph

$$\mathcal{M}^{(i)}_{\text{boxline}} = \mathcal{M}_B^{(i)} F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4\pi^2}{3} - 8 \right]$$

$$+ \frac{\alpha_s(\mu_R)}{4\pi} C_F \widetilde{\mathcal{M}}_\tau(q_1, q_2)(-e^2) g_\tau^{V_1 f_1} g_\tau^{V_2 f_2}$$

$$+ \mathcal{O}(\epsilon)$$

with $F(Q) = \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2}\right)^\epsilon \Gamma(1+\epsilon)$

$\widetilde{\mathcal{M}}_\tau(q_1, q_2) = \widetilde{\mathcal{M}}_{\mu\nu} \epsilon_1^\mu \epsilon_2^\nu$ is universal virtual $qqVV$ amplitude: use like HELAS calls in MadGraph

Handling of IR and collinear divergences

Use tensor decomposition a la Passarino-Veltman

Split $B_0 \quad \cdots \quad D_{ij}$ functions into divergent and finite parts

With $s = (q_1 + q_2)^2$, $t = (k_2 + q_2)^2 = (k_1 - q_1)^2$ we get, for example,

$$B_0(q^2) = \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{\epsilon} + 2 - \ln\frac{q^2 + i0^+}{s} + \mathcal{O}(\epsilon)\right]$$

$$= \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{\epsilon} + \widetilde{B}_0(q^2) + \mathcal{O}(\epsilon)\right]$$

$$D_0(k_2, q_2, q_1) = \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left[\frac{1}{st}\left(\frac{1}{\epsilon^2} + \frac{1}{\epsilon}\ln\frac{q_1^2 q_2^2}{t^2}\right) + \widetilde{D}_0(k_2, q_2, q_1) + \mathcal{O}(\epsilon)\right]$$

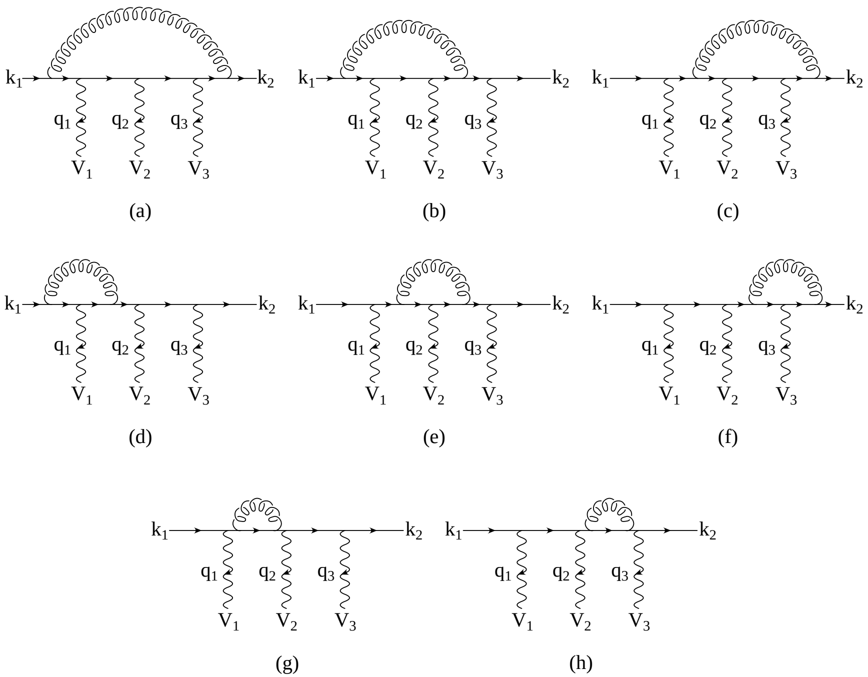
$$D^{\mu\nu}(k_2, q_2, q_1) = \frac{\Gamma(1+\epsilon)}{(-s)^\epsilon}\left(\frac{1}{\epsilon}\left(k_1^\mu k_1^\nu d_2(q_1^2, t) + k_2^\mu k_2^\nu d_2(q_2^2, t)\right) + \widetilde{D}^{\mu\nu}(k_2, q_2, q_1) + \mathcal{O}(\epsilon)\right)$$

with $d_2(q^2, t) = 1/(s(q^2 - t)^2)\,\left[t \ln(q^2/t) - (q^2 - t)\right]$

Finite $\widetilde{D}_{ij}$ have standard PV recursion relations $\Longrightarrow$ determine them numerically

Extension to $qqVVV$ amplitude: pentline 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

$$
\begin{aligned}
\mathcal{M}_V^{(i)} &= \mathcal{M}_B^{(i)} \frac{\alpha_s(\mu_R)}{4\pi} C_F \left(\frac{4\pi\mu_R^2}{Q^2} \right)^{\epsilon} \Gamma(1+\epsilon) \\
&\quad \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + c_{\text{virt}} \right] \\
&\quad + \widetilde{\mathcal{M}}^{(i)}_{V_1 V_2 V_3, \tau}(q_1, q_2, q_3) + \mathcal{O}(\epsilon)
\end{aligned}
$$

- Divergent terms sum to Born sub-amplitude
- Use amplitude techniques to calculate finite remainder of virtual amplitudes

Denner-Dittmaier reduction of pentagon tensors is stable: indication of numerical problems for less than 0.2% of phase space points

Virtual corrections

Born sub-amplitude is multiplied by same factor as found for pure vertex corrections
$\Rightarrow$ when summing all Feynman graphs the divergent terms multiply the complete $\mathcal{M}_B$

Complete virtual corrections

$$\mathcal{M}_V \quad = \quad \mathcal{M}_B \;\; F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4\pi^2}{3} - 8 \right] + \widetilde{\mathcal{M}}_V$$

where $\widetilde{\mathcal{M}}_V$ is finite, and is calculated with amplitude techniques.
The interference contribution in the cross-section calculation is then given by

$$2\,\mathrm{Re}\,[\mathcal{M}_V \mathcal{M}_B^*] = |\mathcal{M}_B|^2 F(Q) \left[-\frac{2}{\epsilon^2} - \frac{3}{\epsilon} + \frac{4\pi^2}{3} - 8 \right] + 2\,\mathrm{Re}\left[\widetilde{\mathcal{M}}_V \mathcal{M}_B^* \right]$$

The divergent term, proportional to $|\mathcal{M}_B|^2$, cancels against the subtraction terms
which have the same structure as for single W or Z production.

Gauge invariance tests

Numerical problems flagged by gauge invariance test: use Ward identities for pentline and boxline contributions

$$q_2^{\mu_2}\widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_1,q_2,q_3) = \widetilde{\mathcal{D}}_{\mu_1\mu_3}(k_1,q_1,q_2+q_3) - \widetilde{\mathcal{D}}_{\mu_1\mu_3}(k_1,q_1+q_2,q_3)$$

With Denner-Dittmaier recursion relations for E_{ij} functions the ratios of the two expressions agree with unity (to 10% or better) at more than 99.8% of all phase space points.

Ward identities reduce importance of computationally slow pentagon contributions when contracting with $W^{\pm}$ polarization vectors

$$J_{\pm}^{\mu} = x_{\pm}\, q_{\pm}^{\mu} + r_{\pm}^{\mu}$$

choose $x_{\pm}$ such as to minimize pentagon contribution from remainders $r_{\pm}$ in all terms like

$$J_{+}^{\mu_1} J_{-}^{\mu_2} \widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_+,q_-,q_0) = r_{+}^{\mu_1}\, r_{-}^{\mu_2}\, \widetilde{\mathcal{E}}_{\mu_1\mu_2\mu_3}(k_1,q_+,q_-,q_0) + \text{box contributions}$$

Resulting true pentagon piece contributes to the cross section at permille level $\Longrightarrow$ totally negligible for phenomenology

Available calculations of VVV cross sections

- QCD corrections to ZZZ production without Higgs-contribution and leptonic decays.
  [Lazopoulos, Melnikov, Petriello; hep-ph/0703273]

- Calculation of QCD corrections to ZZZ, W^+W^-Z, $W^+W^-W^+$ and ZZW^+ production without Higgs-contribution and leptonic decays.
  [Binoth, Ossola, Papadopoulos, Pittau; arXiv:0804:0350]

- QCD corrections to W^+W^-Z production with leptonic decays and Higgs exchange.
  [Hankele, DZ; arXiv:0712.3544]

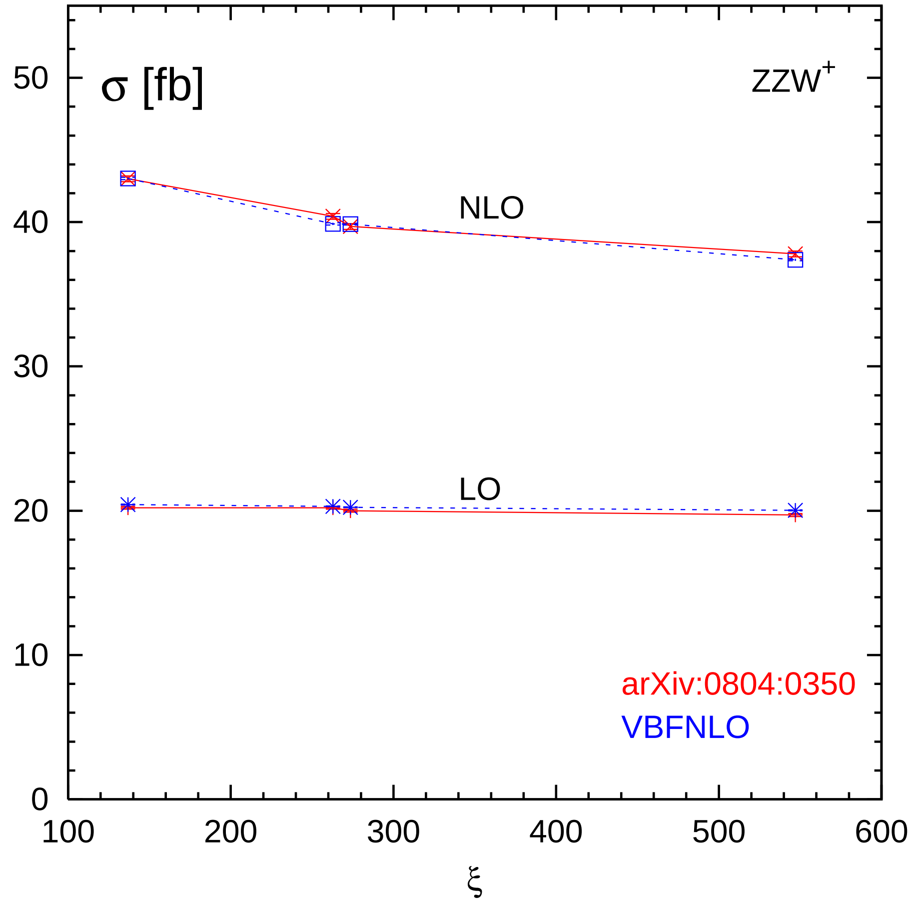
- QCD corrections to $ZZW^\pm$ and $W^\pm W^\mp W^\pm$ production with leptonic decays and Higgs graphs.
  [Campanario, Hankele, Oleari, Prestel, DZ; arXiv:0809.0790]

Implemented into the Fortran program `VBFNLO`.

2008 release includes triple weak boson production: arxiv:0811.4559

Comparison of various tri-boson codes

Numerous checks on the final results. For example comparison of ZZW^+ in narrow width approximation and without Higgs contribution with [Binoth, Ossola, Papadopoulos, Pittau; arXiv:0804:0350]



⇒ Agreement at the level of the accuracy of the Monte Carlo runs.

Input variables for LHC phenomenology

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

- **Cuts and Masses**:

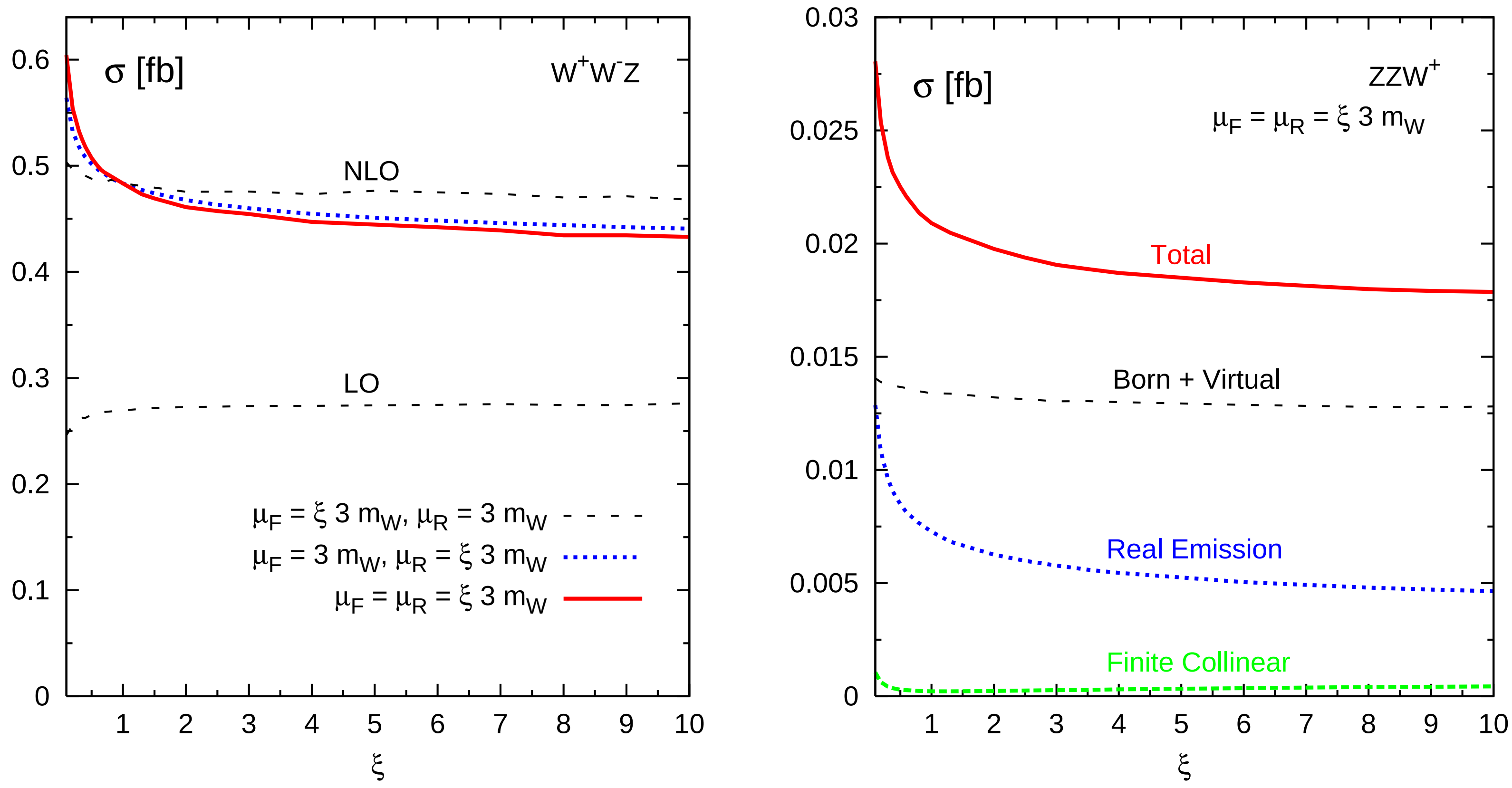
$$p_{T_\ell} > 10 \text{ GeV}, \qquad |\eta_\ell| < 2.5, \qquad m_{\ell^+\ell^-} > 15 \text{ GeV}, \qquad m_H = 120 \text{ GeV}.$$

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

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

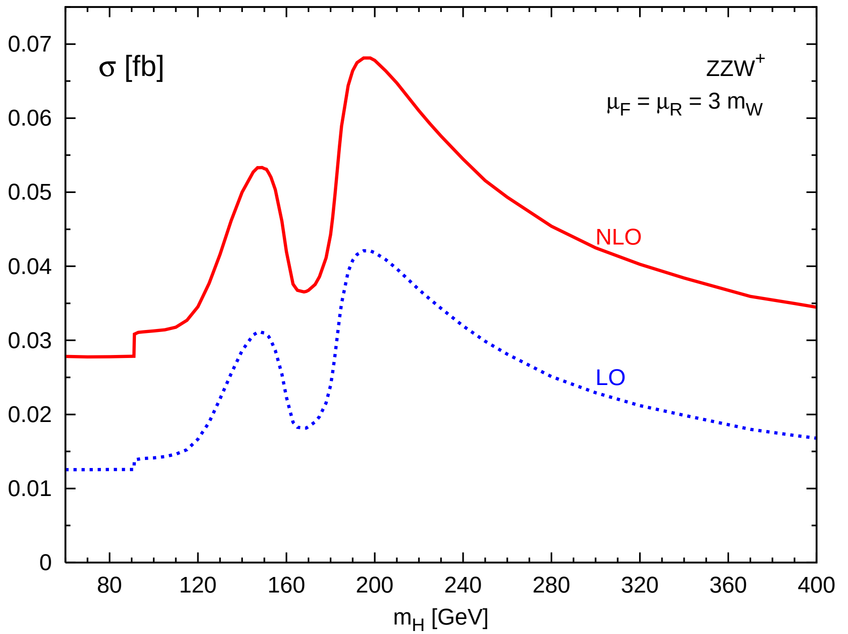
$\Longrightarrow$ Combinatorial factor of 8/4 for the $W^+W^-Z/ZZW^\pm$ production compared to three different lepton families in the final state.

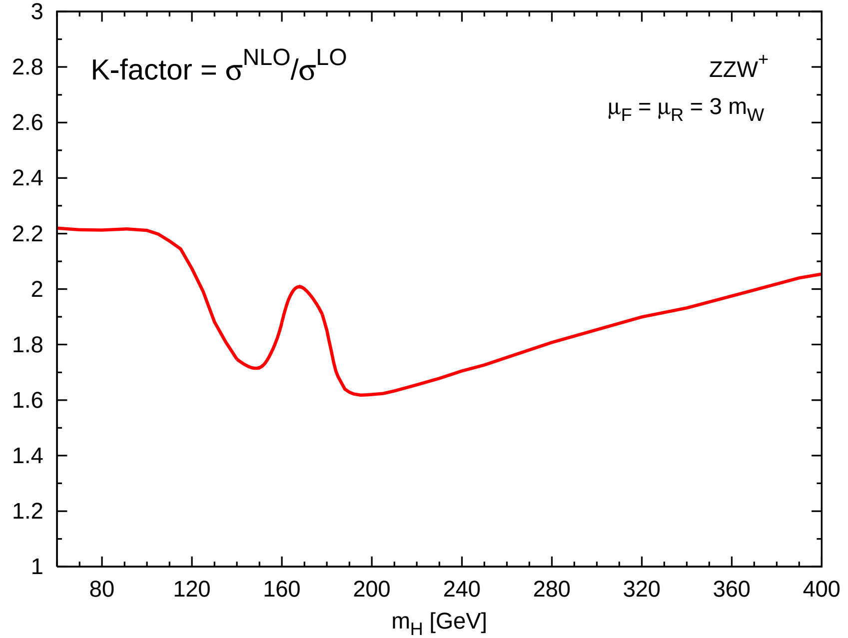
Scale Dependence

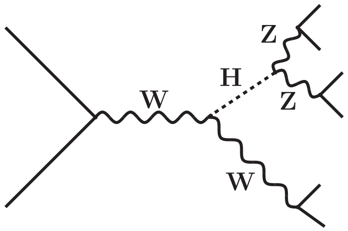


- At LO only small μ_F-dependence, no $\alpha_s(\mu_R)$.
- At NLO scale dependence is dominated by $\alpha_s(\mu_R)$.
- Real emission contribution drives overall scale dependence at NLO.

Higgs mass dependence

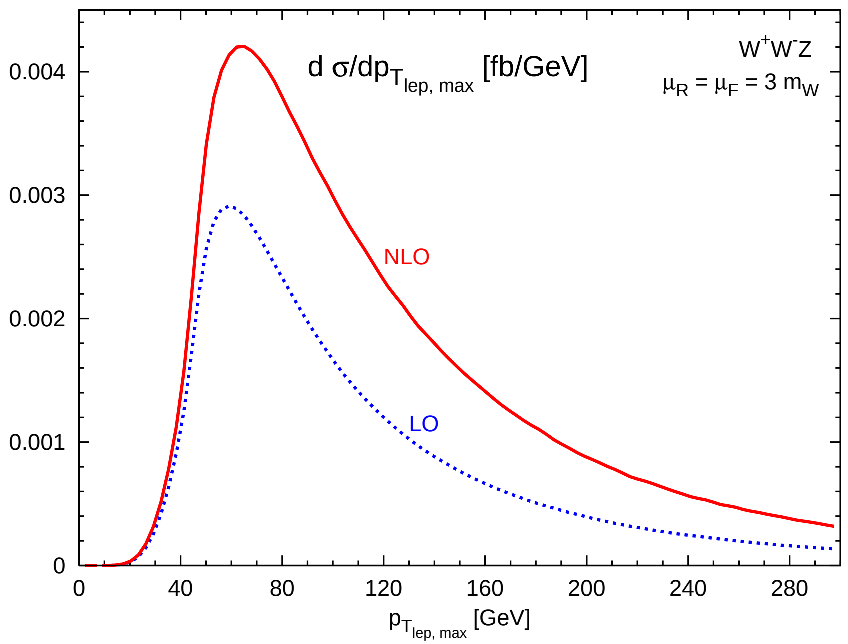


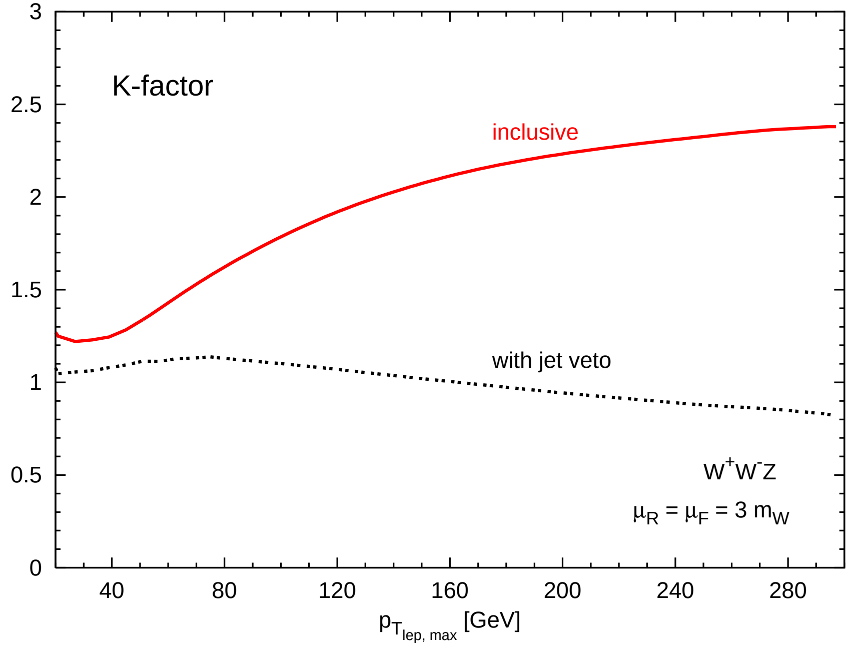




- Cross section reflects behavior of $BR(H \to ZZ)$
- K-factor is reduced by Higgs contribution.
  K-factor for $pp \to ZH$ production is about K = 1.3
  [Han and Willenbrock, Phys. Lett. B **273** (1991) 167.]

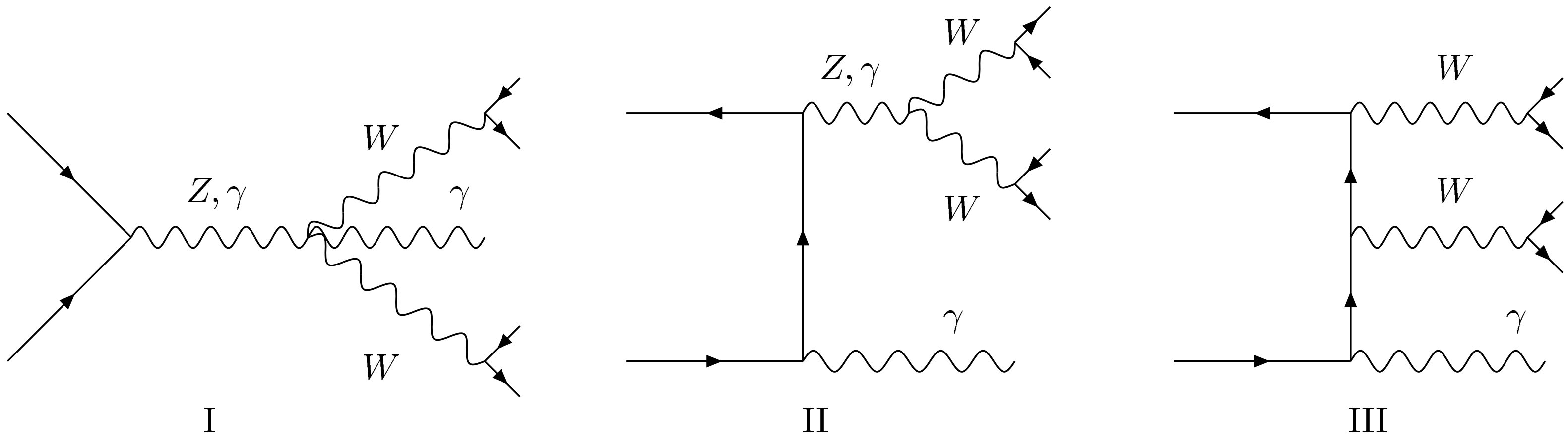
Differential cross section and K-factor for the highest-p_T-lepton





- K-factor increases with transverse momentum (p_T) by almost a factor of 2.
- Strong phase space dependence due to events with high p_T jets recoiling against the leptons.
- Veto on jets with $p_T > 50$ GeV leads to fairly flat K-factor.

Extension to $W^+W^-\gamma$ and $ZZ\gamma$ Production



New elements of calculation:

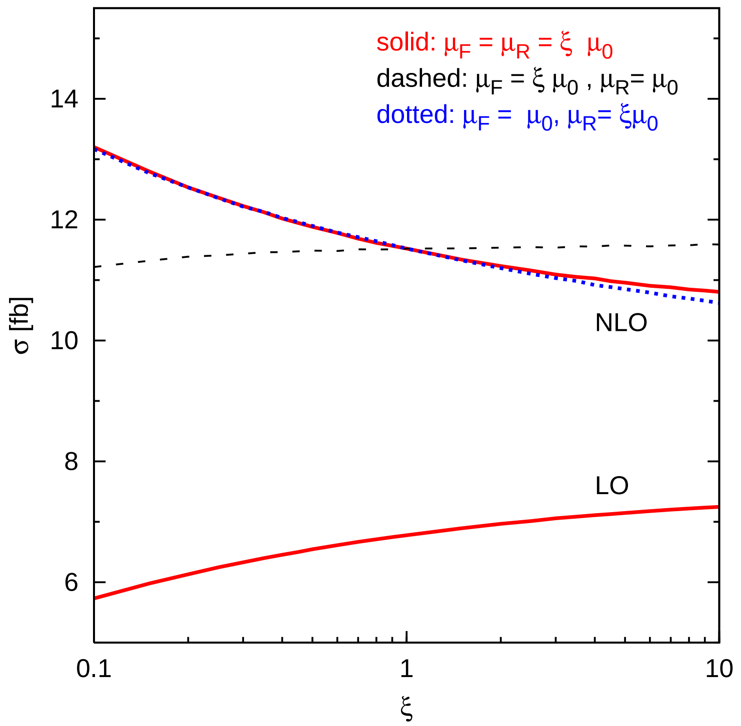
- Different infrared divergence structure of individual loop integrals but same final virtual expressions in terms of finite parts of C_{ij}, D_{ij}, and E_{ij} functions
- Photon isolation from jets for real emission contributions: use Frixione isolation

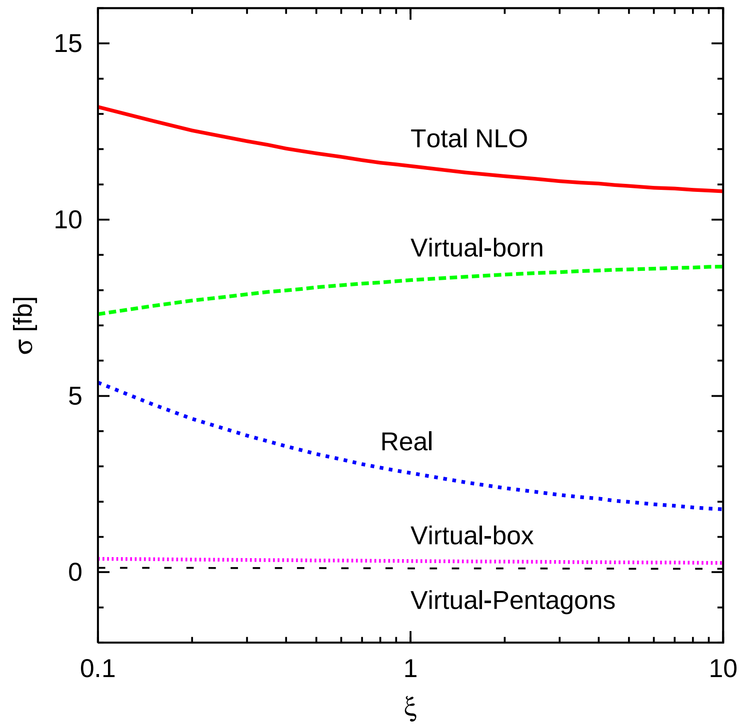
$$\Sigma_i E_{T_i} \theta(\delta - R_{i\gamma}) \leq p_{T_\gamma} \frac{1-\cos\delta}{1-\cos\delta_0} \qquad (\text{for all} \quad \delta \leq \delta_0)$$

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

Scale dependence of integrated cross sections

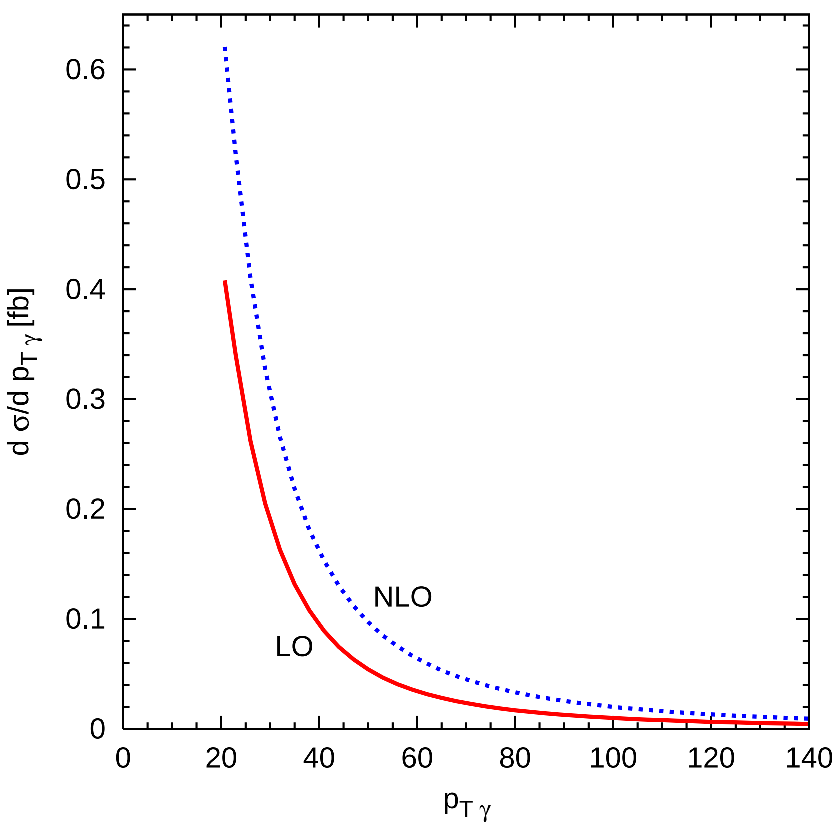
Variation of μ_F, μ_R about $\mu_0 = m_{WW\gamma}$

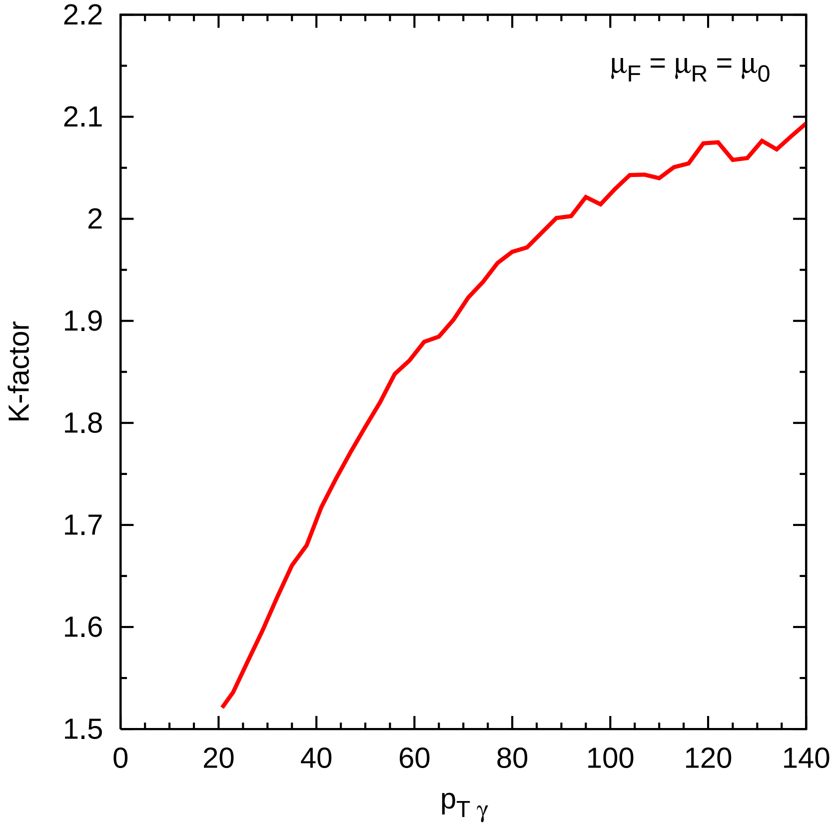




- Behaviour similar to VVV production: LO scale variation much smaller than NLO correction
- NLO scale dependence largely due to real emission contributions $\Longrightarrow$ jet veto will reduce it
- Box and pentagon contributions ($\tilde{\mathcal{M}}_V$ terms) are quite small: 3% and $< 1\%$ of total

NLO Corrections to Distributions: p_T of photon





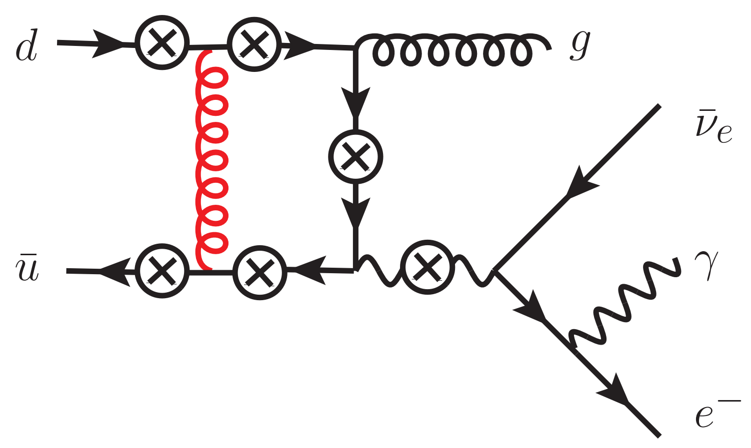
Strong phase space dependence of K-factors (depends on LO scale choice)

NLO QCD Corrections to $W\gamma j$ Production

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

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

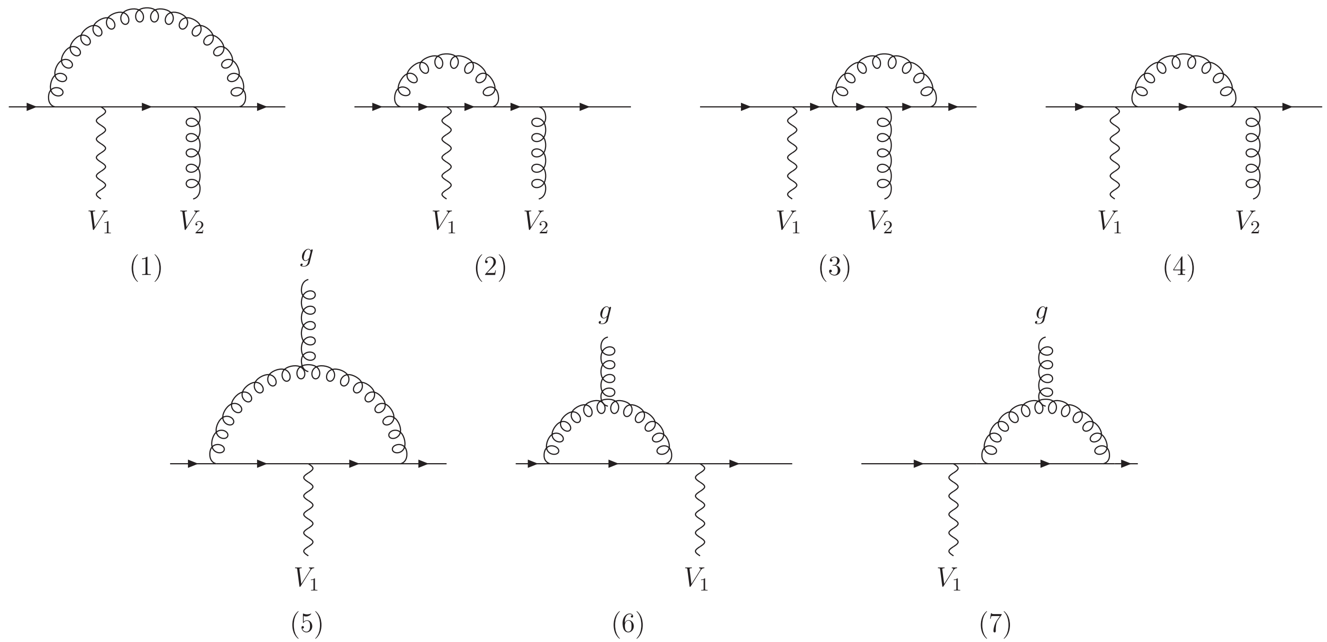
- Sizable cross section at LHC (1.2 pb) and Tevatron (15 fb) for $p_{Tj}, p_{T\gamma} > 50$ GeV and separation cuts (later)
- Measurement of anomalous $WW\gamma$ coupling: veto on jets in $W\gamma$ events requires good knowledge of cross section and distributions: want NLO
- Photon isolation à la Frixione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

Virtual Corrections: nonabelian Contributions

Example: non-abelian extension of boxline graphs. Keep modular structure of calculation



$$\left(C_F - \frac{1}{2}C_A\right) \left(A_1(12) + A_3(12)\right)$$

$$+C_F \quad \left(A_2(12) + A_4(12)\right)$$

$$C_A \left(A_5 + A_6 + A_7\right)$$

Combine to two boxline amplitudes $M_V(12)$ and $M_V(21)$ and new nonabelian combination

$$M_V(12, boxline) = (C_F - \frac{1}{2}C_A) \sum_{i=1,4} A_i(12)$$

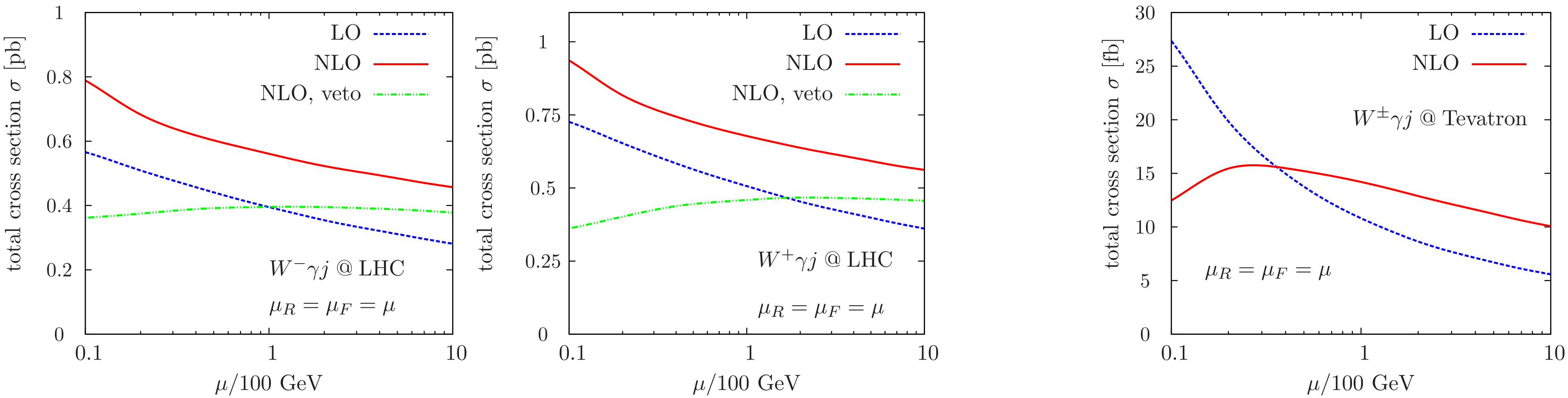
$$M_V(na) = \frac{1}{2}C_A\left(A_2(12) + A_4(12) + A_2(21) + A_4(21)\right) + C_A \left(A_5 + A_6 + A_7\right)$$

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

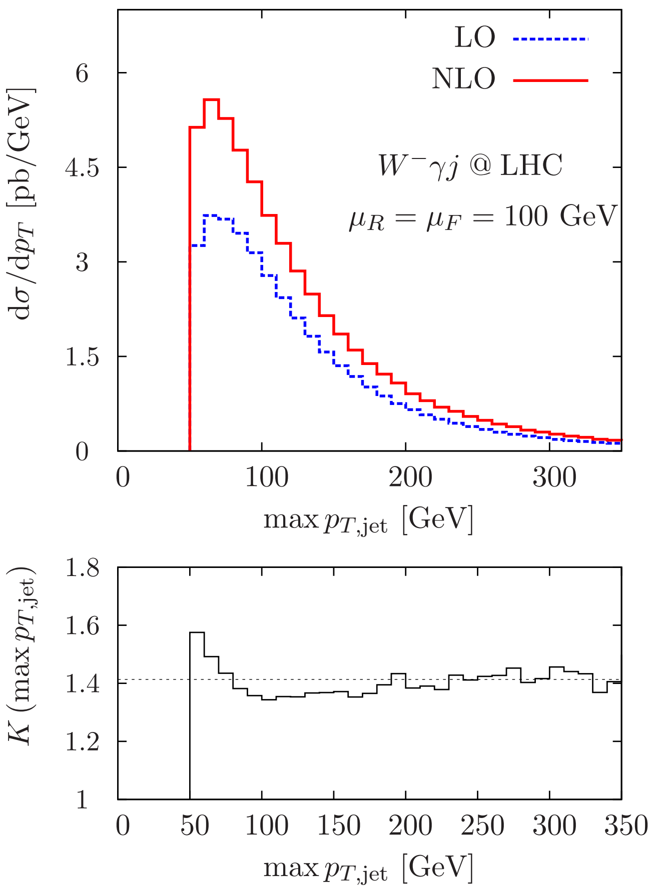


Scale variation at LHC for $\mu_F = \mu_R = 2^{\pm 1} \cdot 100$ GeV: ±11% at LO reduced to ±7% at NLO

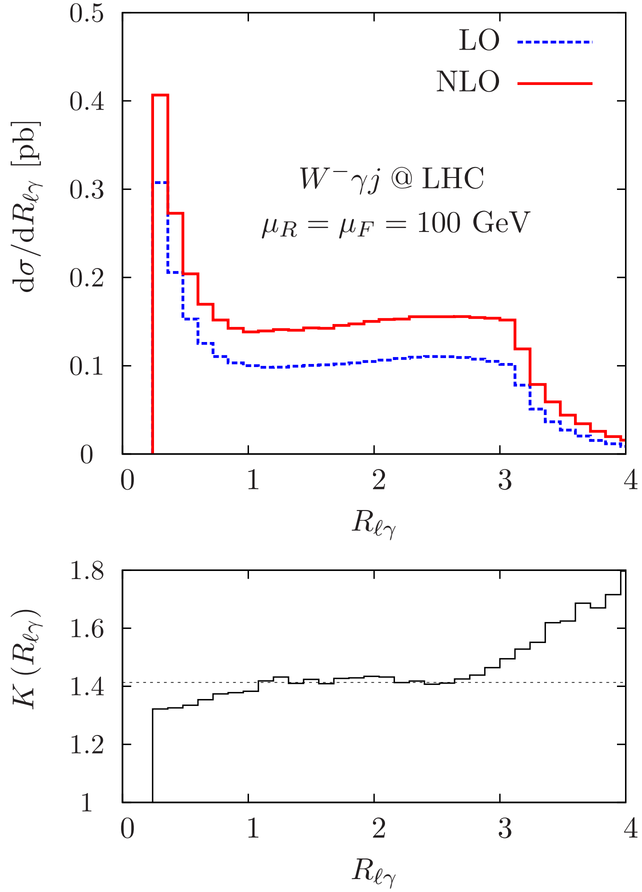
Almost flat behaviour for veto of additional jets of $p_T > 50$ GeV should be taken as accidental and not as a measure of NLO uncertainties

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

Conclusions

- NLO QCD corrections to $pp \rightarrow$ VVV + X are Standard Model background processes for new-physics searches and are sensitive to quartic electroweak couplings.
- All off-shell diagrams as well as the Higgs-contributions have been considered.
- New results for $WW\gamma$ and $ZZ\gamma$ production will appear soon.
- First results on $W\gamma j$ production at NLO have been published in EPL.
- Latest release of `VBFNLO` includes NLO QCD corrections for W^+W^-Z, $ZZW^\pm$ and $W^\pm W^\mp W^\pm$ production at hadron colliders: arxiv:0811.4559

  Code is available at
  http://www-itp.particle.uni-karlsruhe.de/~vbfnloweb
- VBFNLO is collaborative effort! Thanks to
  V. Hankele, B. Jäger, M. Worek, C. Oleari, K. Arnold, G. Bozzi, F. Campanario, C. Englert, T. Figy, G. Klämke, M. Kubocz, S. Plätzer, S. Prestel, M. Rauch, H. Rzehak, M. Spannowsky