NLO QCD corrections to processes with multiple electroweak bosons

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The VBFNLO program package is a collection of Monte Carlo programs for the calculation of NLO QCD corrections to vector boson fusion cross sections, double and triple vector boson production, or the production of two electroweak bosons in association with an additional jet. An overview is given of the processes and features implemented in VBFNLO. $WW\gamma$ and $W\gamma j$ production are discussed as examples.

RADCOR 2009 - 9th International Symposium on Radiative Corrections (Applications of Quantum Field Theory to Phenomenology)
October 25-30 2009
Ascona, Switzerland

1. Introduction

The highest energy particle interactions which can be studied in the laboratory are being provided by $p\bar{p}$ collisions at the Fermilab Tevatron and pp collisions at the CERN Large Handron Collider (LHC). In order to compare hadron collider data with theoretical predictions at a sufficiently precise level, NLO QCD corrections are needed for many signal and background processes. A sizable fraction of these proceedings is devoted to this topic.

The purpose of the present contribution is to provide an overview of NLO QCD calculations which have been implemented in the publicly available VBFNLO [1] program package [1] or which have recently been performed in the VBFNLO framework. In addition, we discuss NLO QCD corrections to $WW\gamma$ production [2] in Section 3 and to $W\gamma j$ production [3] in Section 4.

2. Overview of VBFNLO Processes

The VBFNLO package provides parton level Monte Carlos for the calculation of hadron collider cross sections and distributions with NLO QCD accuracy. The cancellation of collinear and soft divergences between virtual contributions and real emission corrections is achieved with the dipole subtraction method of Catani and Seymour [4]. The calculation of matrix elements is based on the helicity amplitude formalism of Ref. [5], while dedicated routines using Passarino-Veltman and/or Denner-Dittmaier recursion [6] are providing numerical tensor reduction and the calculation of the finite parts of virtual amplitudes.

VBFNLO originates from vector boson fusion (VBF) processes which can be pictured as quark-(anti)quark scattering via t-channel electroweak boson exchange, with the emission of additional weak bosons or a Higgs boson off the quark- or electroweak boson lines. All processes, which are discussed below, neglect identical fermion effects. For VBF processes such as $q\bar{Q} \to q\bar{Q}H$ this implies that s-channel diagrams such as $u\bar{u} \to ZH \to u\bar{u}H$ are considered to be separate processes which are not provided by VBFNLO. Indeed, in the phase space regions where VBF processes can be isolated at the LHC, these s-channel contributions are usually small and their interference with the VBF diagrams is truly negligible (see e.g. Ref. [7]). The following VBF processes at NLO QCD are implemented in the 2008 release of VBFNLO [1]:

- **Hjj** production with and without decay of the Higgs boson [8]. Options for Higgs decay modes include $H \to \tau^+\tau^-$, $H \to W^+W^- \to l^+\nu l^-\bar{\nu}$, $H \to ZZ \to 4$ leptons, $H \to \gamma\gamma$, or $H \to b\bar{b}$. Also, anomalous HVV couplings are supported [9].

- **Hjjj** production with and without decay of the Higgs boson [10]. Options for Higgs decay modes are the same as for Hjj production. The $H + 3$-jet calculation does not contain the full NLO QCD corrections but neglects certain t-channel color exchange contributions which are subleading in $1/N$ and which have been shown to be very small for VBF kinematics.

- **W$^{\pm}$jj** production with subsequent leptonic W decay [11].

- **Zjj** production with subsequent leptonic Z decay [11].

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[1]The source code for the VBFNLO programs is available at http://www-itp.particle.uni-karlsruhe.de/vbfnlo/

- **W⁺W⁻jj** production with subsequent leptonic *W* decay and full off-shell effects [12]. Anomalous trilinear and quartic couplings between Higgs boson and weak bosons are implemented.

- **ZZjj** production with subsequent leptonic *Z* decay and full off-shell effects [14].

- **W±Zjj** production with subsequent leptonic weak boson decay and full off-shell effects [15].

For the last three processes ($VVjj$ production in VBF) extra vector resonances in VV scattering are implemented within the context of warped Higgsless models [13]. Beyond the VBF processes listed above, the calculation of

- **W⁺W⁺jj** and **W⁻W⁻jj** production in VBF with leptonic decay of the *W*s and full off-shell effects [16]

has recently been completed and will be made publicly available in a future VBFNLO release.

The next large class of processes concerns double and triple electroweak boson production with NLO QCD accuracy. At tree level, the underlying reactions are of the type $q\bar{q} \to VV$ or $q\bar{q} \to VVV$. In all cases, leptonic decays of the electroweak bosons to lepton pairs and off-shell effects are included in the calculations. The processes implemented in the 2008 release are

- **W⁺W⁻** production. This process has been verified against MCFM [17].

- **W⁺W⁻Z** production, including the $H \to WW$ resonance [18].

- **W±ZZ** production, including the $H \to ZZ$ resonance [19].

- **W±W∓W±** production, including the $H \to WW$ resonances [19].

Total NLO cross sections for the last three processes (VVV production) have been successfully compared against the results of Ref. [20] which, however, are only available without leptonic decay of the weak bosons and which do not include Higgs resonance contributions.

Two extensions of the triple weak boson production processes have recently been completed within the VBFNLO framework. These are

- **W⁺W⁻γ** and **ZZγ** production with subsequent *W* and *Z* leptonic decay [2] and

- **W±γj** production with $W \to l\nu$ decay [3].

They will be discussed in more detail below.

3. $WW\gamma$ **Production**

The three classes of Feynman graphs contributing to $WW\gamma$ production at tree level are shown in Fig. 3. As in all VBFNLO processes, the decay of the *W*s to charged leptons is included, i.e. the QCD corrections are calculated for the full process $pp, p\bar{p} \to \nu_1 l_1^+ \bar{\nu}_2 l_2^- \gamma + X$, including final state photon radiation off the charged leptons or other off-shell contributions.

Virtual QCD corrections can be considered separately for each of the tree level graphs. Corrections to the vertex topology (I) factorize in terms of the corresponding Born amplitude, and this
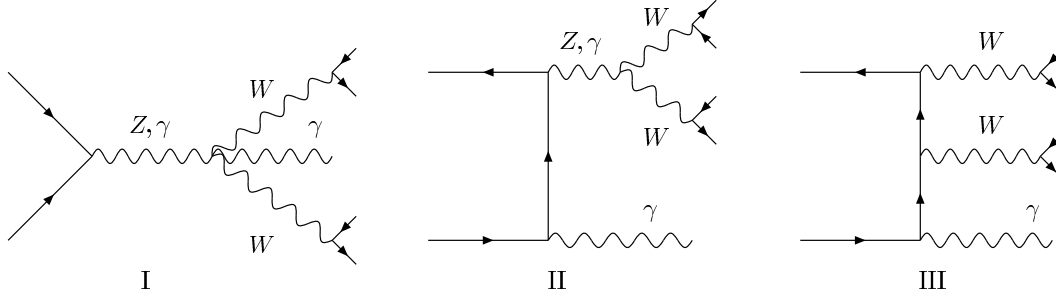
Figure 1: Examples of the three topologies of Feynman diagrams contributing to $pp \to W^+ W^- \gamma + X$.

includes the soft and collinear divergences which appear as $1/\varepsilon^2$ and $1/\varepsilon$ poles in dimensional regularization. The cancellation of these poles against the real emission cross sections, where the divergent phase space integral is proportional to the full Born amplitude squared, implies that the infrared divergent parts of the QCD loop corrections to topologies (II) and (III) also factorize in terms of their respective Born amplitude. The full virtual contributions are thus given by

$$M_V = \widetilde{M}_V + \frac{\alpha_S}{4\pi} C_F \left(\frac{4\pi\mu^2}{Q^2}\right)^\varepsilon \Gamma(1+\varepsilon) \left[-\frac{2}{\varepsilon^2} - \frac{3}{\varepsilon} - 8 + \frac{4\pi^2}{3}\right] M_B, \tag{3.1}$$

where M_B is the Born amplitude and Q is the partonic center-of-mass energy, i.e. the invariant mass of the final state $WW\gamma$ system, $m_{WW\gamma}$. The term $\widetilde{M}_V$ consists of the finite parts of the virtual corrections to 2 and 3 weak boson amplitudes and can be calculated numerically in $d = 4$ dimensions.

For our numerical results we impose a set of minimal cuts on leptons, photon and jets, namely

$$p_{T_{\gamma(\ell)}} > 20\,\text{GeV} \qquad |y_{\gamma(\ell)}| < 2.5 \qquad R_{\ell\gamma} > 0.4 \qquad R_{j\ell} > 0.4 \qquad R_{j\gamma} > 0.7 \tag{3.2}$$
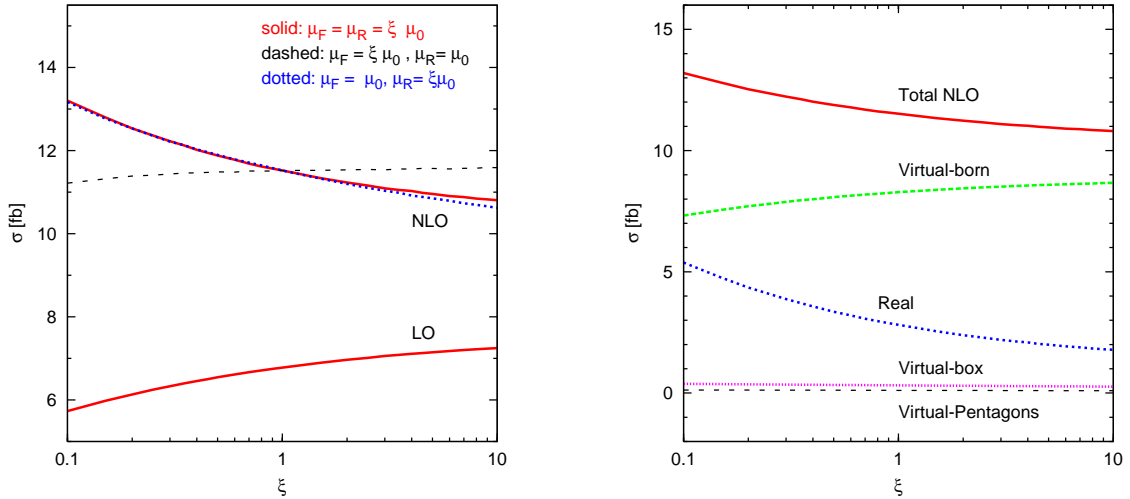

Figure 2: *Left:* Scale dependence of the total LHC cross section for $pp \to W^+ W^- \gamma + X \to \ell^+ \ell^- \gamma + p\!\!\!/_T + X$ at LO and NLO within the cuts of Eqs. (3.2) and (3.3). The factorization and renormalization scales are together or independently varied in the range from $0.1\mu_0$ to $10\mu_0$, with $\mu_0 = m_{WW\gamma}$. *Right:* Same as in the left panel but for the different NLO contributions at $\mu_F = \mu_R = \xi\mu_0$.

where, in our simulations, a jet is defined as a parton of transverse momentum $p_{Tj} > 20$ GeV. For photon isolation, we implement the procedure defined in [21]: if i is a parton with transverse energy E_{T_i} and a separation $R_{i\gamma}$ with a photon of transverse momentum $p_{T\gamma}$, then for

$$\Sigma_i E_{T_i}\,\theta(\delta - R_{i\gamma}) \leq p_{T\gamma}\,\frac{1-\cos\delta}{1-\cos\delta_0} \quad (\text{for all } \delta \leq \delta_0) \tag{3.3}$$

the event is accepted. Here δ_0 is a fixed separation that we set equal to 0.7.

The integrated cross section within these cuts and its scale variation around $\mu_0 = m_{WW\gamma}$ is depicted in Fig. 2. The scale variation is modest both at LO and at NLO. The LO factorization scale variation seriously underestimates the NLO corrections, which amount to a *K*-factor of about 1.7 at the LHC. At NLO, the factorization scale dependence is substantially reduced when compared to LO. The modest renormalization scale dependence can be associated to mainly the real emission contributions.

4. $W\gamma j$ **Production**

In Ref. [3] the NLO QCD corrections to pp, $p\bar{p} \to W^{\pm}\gamma j + X$ cross sections have been calculated, again including final state photon radiation off the W decay products and finite width effects. When varying the factorization and renormalization scales by a factor of 2 around fixed values of $\mu_0 = 100$ GeV one finds modest scale variations which decrease from about 11% at LO to 7% at
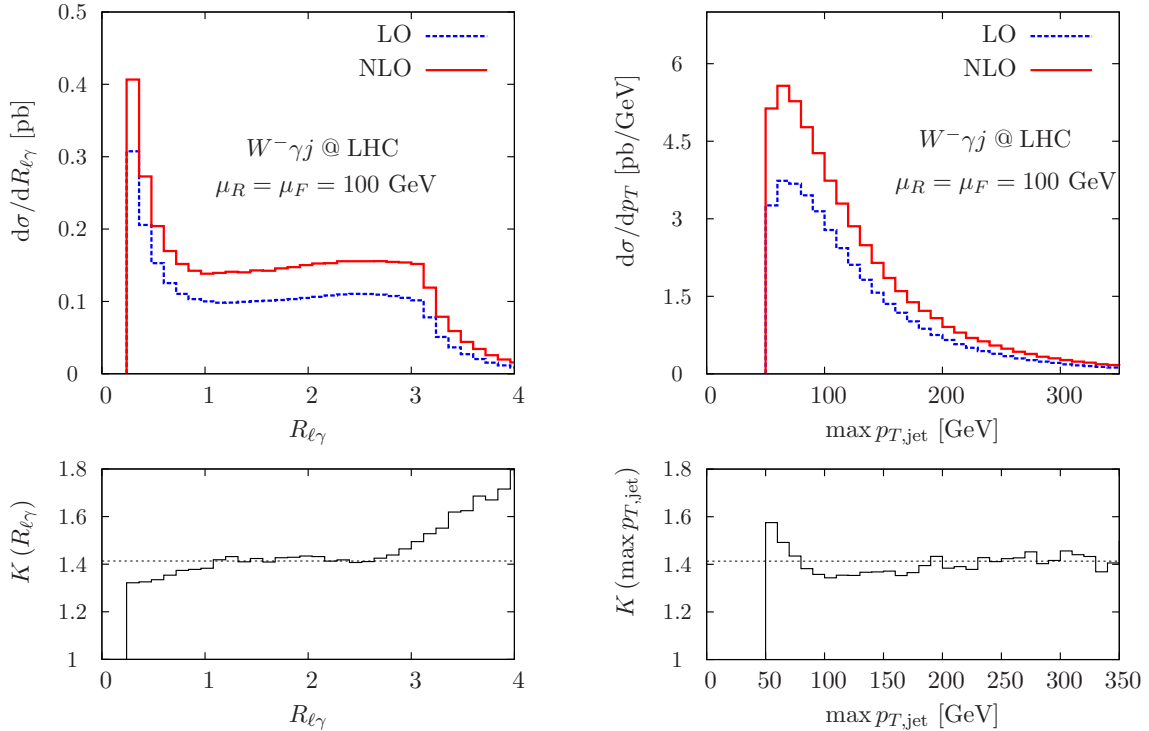

Figure 3: Differential distribution of the photon-lepton separation $R_{\ell\gamma}$ and the maximum jet transverse momentum at LO (dashed) and at NLO (solid). The lower panels show the differential *K*-factor. The dotted lines correspond to the *K*-factor of the integrated cross section, $K = 1.41$.

NLO. *K*-factors are around 1.4 at the LHC, but they do vary over phase space. Two examples for this variation are shown in Fig. 3.

5. Conclusions

For a variety of production processes of electroweak bosons, NLO QCD corrections have been calculated and implemented in the VBFNLO program package. QCD corrections are found to be fairly small for VBF cross sections. For triple electroweak boson production, however, QCD corrections increase LO estimates substantially, by *K*-factors up to 1.8 for integrated cross sections, and even larger values are observed in certain distributions. The size of QCD corrections for $W\gamma j$ production falls between these two extremes. It is clear, however, that NLO QCD corrections should be considered for a precise comparison of data to SM predictions for all these processes.

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