Radiative corrections to $W\gamma\gamma$ production at the LHC

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Radiative W production at hadron colliders is an important testing ground for the Standard Model. We consider $W\gamma\gamma$ production which is sensitive to the quartic $WW\gamma\gamma$ coupling. Furthermore the Standard Model amplitude for this process contains a radiation zero. We present a calculation of the NLO QCD corrections for $W\gamma\gamma$ production at the LHC.

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1. Introduction

With the startup of the LHC the mechanism of electroweak symmetry breaking is accessible to direct experimental investigation. In the Standard Model electroweak symmetry breaking is realized by the Higgs mechanism leading to a single scalar physical state, the Higgs boson. If this description is correct the LHC will be able to discover the Higgs boson and measure some of its properties. It is also possible that the LHC will uncover evidence of physics beyond the Standard Model either by the direct production of new states or by deviations of the couplings of known particles from their Standard Model values.

Anomalous interactions of the known gauge bosons are one interesting possibility and can be studied in gauge-boson production processes. While double gauge-boson production gives access to the triple gauge couplings, triple gauge-boson production processes allow to investigate quartic gauge couplings. The QCD corrections to the production of three heavy gauge bosons have been calculated [1], in some cases including the leptonic decays, and turn out to be fairly large. The corrections to $WW\gamma$ and $ZZ\gamma$ production at the LHC have also become available recently [2] and are sizeable.

Another interesting process is $W\gamma\gamma$ production which is sensitive to both the triple $W\gamma\gamma$ and the quartic $WW\gamma\gamma$ coupling [3, 4]. As already the case for $W\gamma$ production this process exhibits a radiation zero, i.e. the leading order amplitude vanishes exactly for some momentum configurations. The radiation zero in the amplitude appears at a specific polar angle of the W with respect to the incoming quark direction in the partonic centre-of-mass frame if the photons are collinear. This zero will be washed out in practice by the the difficulty in reconstructing the partonic c.m. frame, the unknown incoming quark direction and finite detector resolution effects. Furthermore it could be filled by radiative corrections.

In view of the large radiative corrections for similar processes a full NLO QCD calculation is needed for reliable theoretical predictions. We present the QCD corrections to $W\gamma\gamma$ production at the LHC treating the W as stable, i.e. without including decays of the W. Our calculation has been implemented in a flexible Monte Carlo computer code allowing to calculate arbitrary distributions from a set of weighted events.

2. Calculation

Since we are interested in the anomalous quartic gauge coupling and the radiation zero we focus on the production of two isolated photons accompanying the W. Producing both photons in the hard interaction gives rise to the direct contribution to $pp \rightarrow W\gamma\gamma$. The same final state can also be reached by producing $Wq\gamma$ in the hard interaction followed by a non-perturbative splitting of the quark into a photon. This is described by a fragmentation function $D_{\gamma/q}(z)$ which is formally of $\mathcal{O}(\frac{\alpha}{\alpha_s})$. Both the direct and the fragmentation contribution are therefore formally of the same order in the couplings. In fact only the sum of direct and fragmentation contributions is physically meaningful. In the fragmentation contribution the photon will be accompanied by a collinear hadronic remnant. This contribution can therefore be suppressed by requiring the photons to be isolated which will not affect the direct contribution.

	$\sigma(pp \to W^+ \gamma\gamma)\,[\text{fb}]$		
	standard	with isolation	iso & jet veto
LO direct	7.253(5)	7.253(5)	7.253(5)
LO frag	24.30(2)	1.505(1)	1.501(1)
LO total	31.55	8.758	8.754
NLO	39.33(6)	25.62(4)	11.83(4)
K factor	1.25	2.93	1.35

Table 1: Total cross sections for $pp \to W^+ \gamma\gamma$ at LHC for $\sqrt{s} = 14\,\text{TeV}$ with standard cuts only, with additional photon isolation cuts and with photon isolation and jet veto cuts. Shown are the leading-order direct and fragmentation contributions, the total leading-order cross section, the complete NLO result and the K-factor.

At NLO both the corrections to the direct and the fragmentation contributions are needed in principle. The fragmentation contribution will produce a fragmentation counterterm which cancels the QED singularity from the $q \to q\gamma$ splitting in the real radiation process $qg \to Wq\gamma$. The QED singularity is therefore absorbed into a redefinition of the fragmentation function at NLO. Due to the effective suppression of the fragmentation contribution using photon isolation cuts the NLO corrections to the fragmentation process contribute only little. We therefore take into account only the NLO corrections to the direct contribution. The fragmentation contribution is calculated only at LO but with the NLO fragmentation functions of Ref. [5], i.e. the fragmentation counterterm is included.

The calculation itself has been performed in a diagrammatic approach mostly using standard techniques and tools. For the virtual corrections the generation and simplification of the diagrams has been performed using FEYNARTS [6] and FORMCALC [7]. The analytical results of FORM-CALC have then been translated to C++ code. For the real amplitudes MADGRAPH has been used [8]. In order to extract the soft and collinear singularities from the real corrections and combine them with the virtual contribution we have implemented both a two cutoff phase-space slicing method according to [9] and the dipole subtraction formalism [10].

The tensor 1-loop integrals appearing in the virtual amplitudes are evaluated using a tensor reduction approach. The 5-point integrals are reduced to scalar 4-point functions in a numerically stable way using Ref. [11]. For the 3- and 4-point tensor integrals we employ Passarino-Veltman reduction [12]. In regions of phase space where this becomes unstable we still use the same reduction but switch to high-precision arithmetic using the QD library [13]. Since only a small fraction of the points are unstable the additional time needed by the high-precision evaluations is moderate.

3. Numerical Results

We now turn to the study of some results for $W^+ \gamma\gamma$ production at the LHC for $\sqrt{s} = 14\,\text{TeV}$. To obtain a well-defined cross section we impose the following standard cuts

$$p_{T,\gamma} > 30\,\text{GeV} \qquad |\eta_\gamma| < 2.5 \qquad \Delta R_{\gamma\gamma} > 0.4 \qquad \Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

on the transverse momenta, the pseudorapidities and the separation of the photons. The corresponding cross section and the associated K-factor are shown in Tab. 1. For these cuts the fragmentation
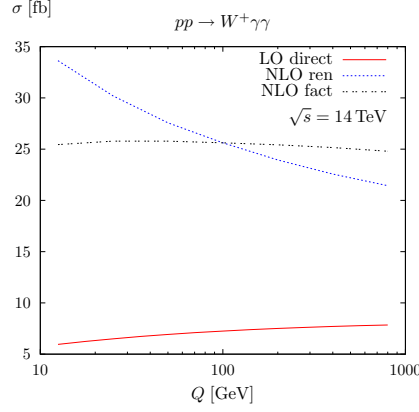
Figure 1: Scale dependence of the direct leading-order and the full NLO cross sections using the standard and photon isolation cuts. No jet veto is applied. The renormalization and factorization scale dependencies of the NLO result are shown separately.

contribution is by far dominant. The NLO corrections are only moderate when compared to the combined LO result. However no corrections to the fragmentation contribution have been taken into account in our calculation.

In order to isolate the direct contribution we impose an additional photon isolation criterion. This is implemented by requiring the hadronic transverse energy inside a cone around the photon to be limited

$$E_{T,had} < \varepsilon E_{T,\gamma} \quad \text{inside cone} \quad \Delta R(\gamma, had) < R_{cone}.$$

We use the energy fraction $\varepsilon = 0.15$ and a cone size of $R_{cone} = 0.7$. As Tab. 1 shows this suppresses the fragmentation contribution by more than an order of magnitude while leaving the direct contribution unchanged. The NLO corrections are very large with a K-factor of 2.93. At NLO quark-gluon and antiquark-gluon induced partonic channels open up in the real corrections which might be responsible for the large corrections.

In order to verify if the large corrections are caused by the real corrections we impose a jet veto in addition to the standard and isolation cuts. We remove all events with the jets fulfilling

$$p_{Tj} > 50 \, \text{GeV} \quad \text{and} \quad |\eta_j| < 3.$$

This leaves the leading order unchanged while greatly reducing the QCD corrections as can be seen from Tab. 1. The corrections are now only 35% and the large corrections seen without jet veto are therefore indeed caused by real radiation.

The scale dependence at leading and next-to-leading order is shown in Fig. 1. Since the LO amplitude does not contain α_s the renormalization scale dependence is increased at NLO. The factorization scale dependence is stabilized however.

In Fig. 2 distributions in the invariant mass $M_{\gamma\gamma}$ of the photons and the transverse W momentum $p_{T,W}$ are shown. The corrections show a shape dependence in both cases. This is especially strong in the $p_{T,W}$ distribution with a K-factor of about 2.5 at $p_T = 20 \, \text{GeV}$ and about 10 at $p_T = 500 \, \text{GeV}$. The effect of the jet veto is to remove the positive corrections at high invariant masses and p_T completely while not affecting the lower regions as much. Regardless of the use of a jet veto the
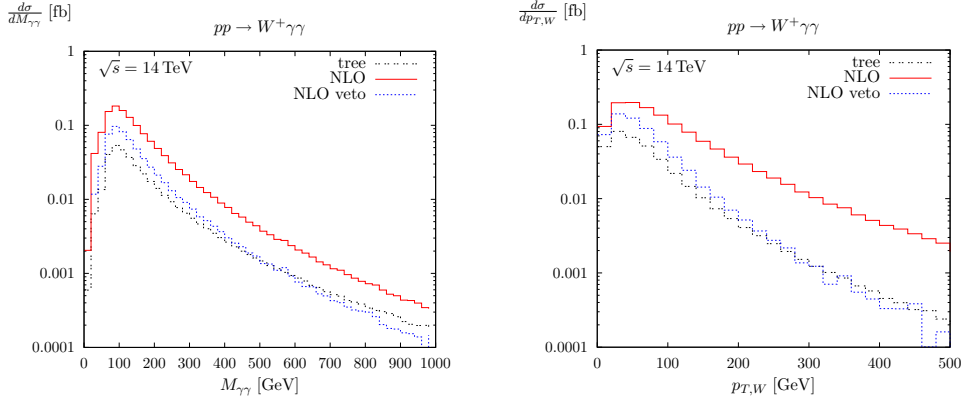
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Figure 2: Distributions in γγ invariant mass and *W* transverse momentum at leading and next-to-leading order using standard and photon isolation cuts. Also shown is the NLO result using an additional jet veto.
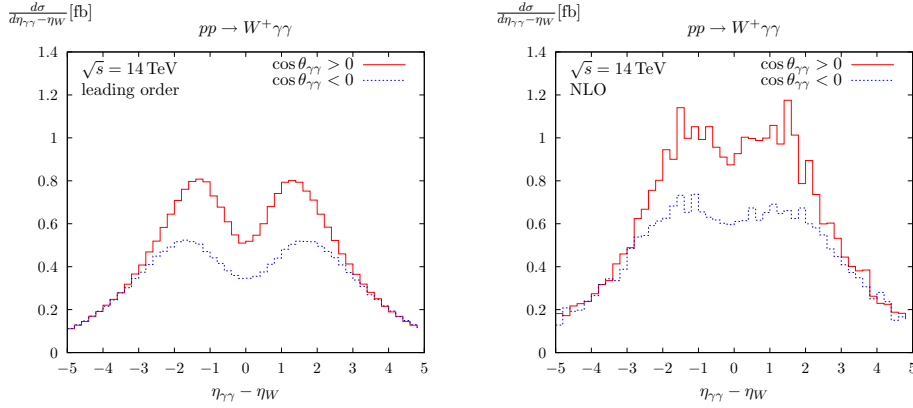

Figure 3: Distributions in pseudorapidity separation between the *W* and the two-photon system for the photons in the same and in opposite hemispheres at leading order (l.h.s) and NLO (r.h.s). Both photon isolation and jet veto cuts have been imposed.

NLO corrections show a strong shape dependence and can therefore not be described by a global K-factor.

To investigate the impact of the NLO corrections on the radiation zero we show the separation in pseudorapidity between the γγ system and the *W* in Fig. 3. To show the radiation zero most clearly not only photon isolation but also jet veto cuts are used. The variable used here is similar to that used for the Tevatron analysis of the radiation zero in Ref. [3]. At leading order a dip at zero pseudorapidity can be seen which is stronger for photons in the same hemisphere since the exact amplitude zero only occurs for collinear photons. The NLO corrections have the effect of almost filling the dip, similar to what has been observed for *W* γ production at the LHC [14]. This will make it very challenging to detect this feature of the amplitude at the LHC.

4. Conclusions

We have calculated the NLO QCD corrections to *W* γγ production at the LHC. This process can be used to constrain the anomalous quartic *WW* γγ gauge couplings and is therefore an important

testing ground of the Standard Model. We have also included the single fragmentation contribution to this process at leading order. The fragmentation contribution can however be effectively suppressed using photon isolation cuts.

We find large radiative corrections of about +200% which reduce to about +35% when using an additional jet veto. The size of the corrections is similar to what has been found in $W\gamma$ and $Z\gamma$ production. As expected the total scale dependence is increased at NLO while the pure factorization scale dependence is stabilized. The corrections induce strong shape distortions in several key distributions. They also tend to fill the dip caused by the radiation zero of the amplitude making it very hard to experimentally verify this feature at the LHC. The calculation has been implemented in a flexible Monte Carlo code which allows to study any distribution using arbitrary cuts.

Acknowledgments

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