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Diphoton production at hadron colliders in NNLO QCD

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We consider higher-order QCD corrections for direct photon pair production in hadron collisions and we present results for the next-to-next-to-leading order (NNLO) calculation at fully differential level. The calculation is based on the q_T-subtraction formalism and it is implemented in a parton level Monte Carlo numerical program. The program allows the user to apply arbitrary infrared-safe kinematical cuts on the final-state photons and on the accompaining jet activity. We show some illustrative numerical results at the LHC and the Tevatron.

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In the search for a low mass Higgs boson ($m_H \lesssim 140$ GeV), the preferred search mode at the LHC involves Higgs boson production via gluon fusion followed by the decay into a pair of photons and the main irreducible background is represented by diphoton production. Beside the relevance for Higgs searches, the production of photon pairs in hadron collisions is a classical Standard Model process and gives important information on the parton densities (in particular the gluon density) of the colliding hadrons.

Because the reasons above, it is essential to have accurate theoretical predictions for the cross section of prompt diphotons with large invariant mass and for the various associated kinematical distributions. Such task require, in particular, detailed computation of radiative corrections.

The next-to-leading order (NLO) QCD corrections at fully-differential level have been computed and implemented in various Monte Carlo codes [1, 2, 3, 4][1]. Part of the next-to-next-to-leading order (NNLO) contribution, the *box contribution* to the *gg* partonic channel, was computed in Ref.[5] and, due to the large gluon–gluon luminosity, its size turns out to be comparable to the leading order (LO) result. The next-order gluonic corrections to the *box contribution* (which are part of the N^{3}LO QCD corrections) were also computed [2] and found to have a moderate effect on the 'NLO+box' result.

Prompt photons (i.e. photons not coming from hadron decay) can be produced by two different mechanism: either *directly* from the hard scattering subprocess or from the *fragmentation* of a QCD parton. The computation of the fragmentation subprocess requires the knowledge of the (poorly known) non-perturbative dominated parton fragmentation functions of the photon.

Experimental detection of prompt photons necessarily requires the application of photon isolation criteria to reject the very large background of secondary photons produced by hadron decays. Isolation criteria sizeably reduce also the size of the fragmentation contributions which have a collinear nature. Two possible isolation criteria are the *standard cone* approach, which can be easily implemented in experiments but it only suppresses a fraction of the fragmentation contribution, and the *smooth cone* approach proposed in Ref. [6] which completely eliminates fragmentation contribution, but its experimental implementation is difficult.

We present the computation of the complete NNLO QCD corrections to direct diphoton production in hadron collisions performed in Ref.[7]. We consider the inclusive hard-scattering process

$$h_1 + h_2 \to \gamma\gamma + X \quad , \tag{1}$$

where h_1 and h_2 are the colliding hadrons, $\gamma\gamma$ is the produced diphoton system with high invariant mass $M_{\gamma\gamma}$, and X is an arbitrary and undetected final state.

We follow the q_T-subtraction formalism proposed in Ref. [8] to handles and cancels the unphysical infrared divergences of the scattering amplitudes. This method applies to the production of a generic colourless high-mass system in hadron collisions, and is based on an extension, up to NNLO, of the subtraction formalism [9] (for details see Ref. [8]).

The key idea of the q_T-subtraction formalism is that the cross section for diphoton production at (N)NLO can be written as:

$$d\sigma^{\gamma\gamma}_{(N)NLO} = \mathscr{H}^{\gamma\gamma}_{(N)NLO} \otimes d\sigma^{\gamma\gamma}_{LO} + \left[d\sigma^{\gamma\gamma+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right] \quad , \tag{2}$$

[1]The calculation in Ref.[4] also includes the effects of transverse-momentum resummation.

where $d\sigma^{\gamma\gamma+\text{jets}}_{(N)LO}$ represents the cross section for diphoton production plus jets at (N)LO order (which was performed at NLO in Ref. [10]), and $d\sigma^{CT}_{(N)LO}$ is a subtraction counterterm whose explicit expression can be obtained from the transverse-momentum resummation program [11]. The 'coefficient' $\mathcal{H}^{\gamma\gamma}_{(N)NLO}$ contains the physical information one-loop (two-loops) virtual correction to the LO subprocess.

The general structure of the coefficient $\mathcal{H}^{F}_{NLO}$ for a generic process F was explicitly derived in Ref. [12]. The general structure of the second order coefficient $\mathcal{H}^{F}_{NNLO}$ at present is not known, we have explicitly calculated $\mathcal{H}^{\gamma\gamma}_{NNLO}$ for diphoton production by using the explicit results of $\mathcal{H}^{F}_{NNLO}$ for Higgs [8, 13] and vector boson [14] production and the relevant scattering amplitudes [15, 16, 17].

Our calculation is encoded in a parton level Monte Carlo program that allow the user to compute the relevant cross sections with arbitrary infrared-safe cuts on the momenta of the photons in the final state and on the associated jet activity.

Since the present formulation of the q_T-subtraction formalism [8] is valid for the production of colourless systems and it does not treat parton fragmentation subprocesses, we consider the direct production of diphotons only and we rely on the smooth cone isolation criterion [6]. In particular we require the total amount of hadronic (partonic) transverse energy E_T inside each cone of radius $r < R$ around each photon to be smaller than $E_T^{max}(r)$,

$$\sum_{\in r} E_T \leq E_T^{max}(r) \equiv \varepsilon_\gamma \, p_T^\gamma \left(\frac{1-\cos r}{1-\cos R} \right)^n , \tag{3}$$

where p_T^γ is the photon transverse momentum and we set the isolation parameters to the values $\varepsilon_\gamma = 0.5$, $n = 1$ and $R = 0.4$.

In the following we present an illustrative selection of numerical result for diphoton production at the LHC and the Tevatron. We use the MSTW2008 [18] sets of parton distributions, with densities and α_S evaluated at each corresponding order (i.e., we use $(n+1)$-loop α_S at N^{n}LO, with $n = 0,1,2$). The renormalization (μ_R) and factorization (μ_F) scales are fixed to the value of the invariant mass of the diphoton system, $\mu_R = \mu_F = M_{\gamma\gamma}$. The QED coupling constant α is fixed to $\alpha = 1/137$.

We start the presentation of our results by considering diphoton production at the LHC ($\sqrt{s} =$ 14 TeV). We require the harder (softer) photon to have a transverse momentum $p_T^{\text{harder}} \geq 40$ GeV ($p_T^{\text{softer}} \geq 25$ GeV). Both photons are required to have a rapidity $|y_\gamma| \leq 2.5$ and their invariant mass is constrained to be in the range $20 \leq M_{\gamma\gamma} \leq 250\,\text{GeV}$.

In Fig. 1 we compare the LO, NLO and NNLO invariant mass distributions (we also plot the gluon-gluon induced *box contribution*). We note that the value of the cross section remarkably increases with the perturbative order of the calculation. This increase is mostly due to the use of *very asymmetric* (unbalanced) cuts on the photon transverse momenta. The LO kinematics implies that the two photons are produced with the same transverse momentum which should be $p_T^\gamma \geq 40$ GeV and the invariant mass of the diphoton system should be $M_{\gamma\gamma} \geq 80$ GeV. At higher orders, the final-state radiation of additional partons opens a new region of the phase space, where $40 \geq p_T^{\text{softer}} \geq 25$ GeV. Since photons are copiously produced with small transverse momentum, the cross section receives a sizeable contribution from the enlarged phase space region. Moreover this effect is enhanced by the opening of a new large-luminosity partonic channel at each perturbative

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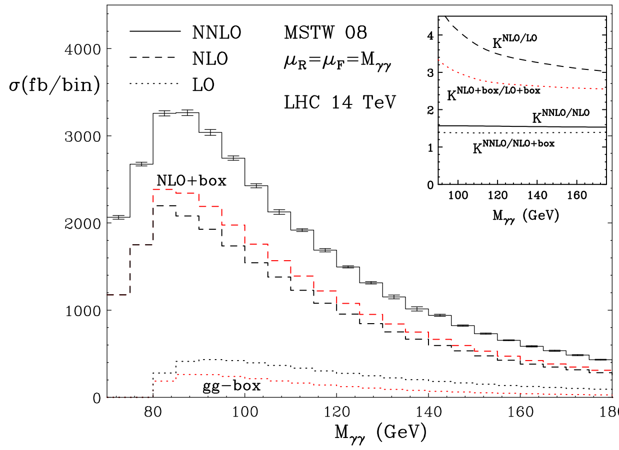

Figure 1: *Invariant mass distribution of the photon pair at the LHC ($\sqrt{s} = 14$ TeV): LO (dots), NLO (dashes) and NNLO (solid) results (the applied kinematical cuts are described in the text). The inset plot shows the corresponding* K*-factors.*

order: the qg channel at NLO (which accounts for about 80% of the increase of the cross section) and the gg channel at NNLO.

The inset plot shows that the NNLO K-factor is sensibly smaller than the NLO one, indicating an improvement in the convergence of the perturbative expansion. In particular, the impact of the full NNLO corrections turns out to be reasonably moderate, being about 35% of the NLO+box distribution. The NNLO calculation includes the perturbative corrections from the entire phase space region (in particular, the next-order correction to the dominant qg channel) and the contributions from all possible partonic channels. For the reasons above the NNLO result can be considered the first reliable estimate of direct diphoton production.

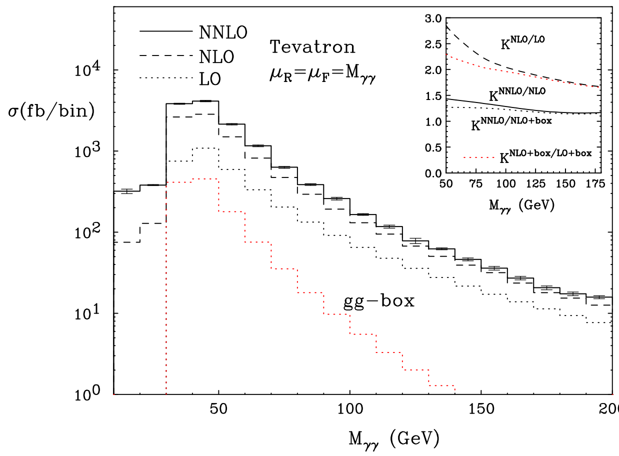

Figure 2: *Invariant mass distribution of the photon pair at the Tevatron ($\sqrt{s} = 1.96$ TeV): LO (dots), NLO (dashes) and NNLO (solid) results (the applied kinematical cuts are described in the text). The inset plot shows the corresponding* K*-factors.*

In Fig. 2, we present the invariant mass distribution for diphoton production at the Tevatron ($\sqrt{s} = 1.96$ TeV). We require the harder (softer) photon to have a transverse momentum larger than

17 GeV (15 GeV) and both photons to have a rapidity $|y_\gamma| \leq 1$. We note that, in this case, the increase from the LO to the NLO result is considerably smaller than in Fig. 1: this is mostly due to the use of photon transverse-momentum cuts that are only slightly asymmetric. In the region where $M_{\gamma\gamma} \gtrsim 80$ GeV, the relative impact of the *box contribution* is smaller than at the LHC: this is a consequence of the higher values of parton momentum fractions that are probed by Tevatron kinematics. Nevertheless, the NNLO corrections still increase the NLO result by roughly 30%.

We have presented a fully-exclusive calculation of the cross section for diphoton production up to the NNLO in QCD perturbation theory. At the NNLO all the $\mathcal{O}(\alpha_S^2)$ corrections are considered, leading to a fully-consistent inclusion of the *gg* channel. The illustrative numerical results show that the NNLO corrections are large (about 30%−40% with respect to the NLO results) and cannot be neglected. Our calculation is directly implemented in a parton level Monte Carlo program which allow the user to compute the kinematical distributions in the form of bin histograms.

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