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Fully differential NNLO QCD calculations for vector boson and *W*-Higgs production at hadron colliders

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In this talk we consider higher-order QCD corrections for Drell-Yan like processes. In particular we present results for next-to-next-to-leading order (NNLO) QCD calculations at fully differential level, for vector boson production and for associated W-Higgs production at hadron colliders. The calculations are based on the q_T-subtraction formalism and are implemented in parton level Monte Carlo numerical programs. The codes allow the user to apply arbitrary (infrared safe) kinematical cuts on the final state leptons and on the accompanying jet activity. We show some illustrative numerical results at the Tevatron and the LHC.

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1. Introduction

In the last years a large amount of experimental data have been accumulated in hadronic collisions at the Tevatron and more precise data are becoming available thanks to the LHC. To fully exploit the discovery power of these data, it is important to have a precise knowledge of the corresponding theoretical cross sections and distributions. In particular this requires the computation of higher-order QCD corrections.

One of the most significant process at hadron colliders is the production of lepton pairs via vector bosons i.e. the Drell-Yan mechanism [1] . This process is important, for instance, to measure the electroweak parameters (as the electroweak mixing angle and the W mass and width), to fit the parton distribution functions (PDFs) and to estimate the background for signals from physics beyond the Standard Model (SM). The QCD corrections for the Drell-Yan process are known up to NNLO for the total cross section [2] and for the rapidity distribution [3] of the vector boson. Two independent fully exclusive numerical calculations are available [4, 5]. Electroweak corrections at order $\mathcal{O}(\alpha)$ have also been computed [6, 7].

The most recent analysis at the Tevatron and the LHC have excluded at 95% CL the SM Higgs boson for all masses except the large mass region, $m_H > 600$ GeV, and the low mass range $115.5 < m_H < 127$ GeV [8, 9, 10]. For low masses, an important Higgs production mechanism is the associated Higgs-W/Z production (with the vector boson decaying leptonically and the Higgs in a $b\bar{b}$ pair). At the Tevatron this is the main search channel, while at the LHC it represents an important alternative to the dominant gluon fusion mechanism. The next-to-leading order (NLO) and the bulk of the NNLO QCD corrections for this process are the same of those of the Drell-Yan process [11]. The non-DY-like NNLO corrections for the total cross section were calculated in Refs. [11, 12, 13] and turn out to be (for $m_H \sim 120$) at the level of about 1% for the WH production and at the level of about 5% for the ZH production (where, contrary to the WH case, some large luminosity gluon-gluon induced terms are present). Electroweak corrections at order $\mathcal{O}(\alpha)$ are also known [14].

2. Vector boson production

We briefly describe the NNLO QCD computation for the Drell-Yan process of Ref. [5]. This calculation was performed using the q_T-subtraction formalism introduced in Ref. [15]. The method is valid for the hadroproduction of colourless high-mass system and it has also been applied for Higgs production [15, 16] and direct diphoton production [17].

Within the q_T-subtraction formalism the NNLO fully differential cross section is schematically written as

$$d\sigma^F_{NNLO} = \mathscr{H}^F_{NNLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jets}}_{NLO} - d\sigma^{CT}_{NLO} \right] \ , \tag{2.1}$$

where $d\sigma^F_{LO}$ is the Born cross section, $d\sigma^{F+\text{jets}}_{(N)LO}$ is the cross section for the production of the system F plus jets at NLO [18] and $d\sigma^{CT}_{NLO}$ is an universal subtraction counter-term which cancels the remaining NNLO singularities at $q_T = 0$. This counter-term is obtained from the resummation program of logarithmically-enhanced contributions to q_T distributions [19]. Finally $\mathscr{H}^F_{NNLO}$ is a process-dependent coefficient function necessary to reproduce the correct normalization [20].

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Our fully differential NNLO calculation for vector boson production includes finite-width effects, the $\gamma - Z$ interference and the leptonic decay of the vector boson with the corresponding spin correlations. The computation is encoded in the parton-level Monte Carlo numerical program `DYNNLO` [21], which allows the user to compute distributions in the form of bin histograms and to apply arbitrary (though infrared safe) kinematical cuts on the final-state leptons and the associated jet activity.

For illustrative purpose we compute the NNLO lepton charge asymmetry from $W^\pm$ decays at the LHC [22], which is defined in term of the charged lepton ($l^\pm$) pseudorapidity (η_l) distribution $d\sigma(l^\pm)/d\eta_l$ as

$$A(\eta_l) = \frac{d\sigma(l^+)/d\eta_l \, - \, d\sigma(l^-)/d\eta_l}{d\sigma(l^+)/d\eta_l \, + \, d\sigma(l^-)/d\eta_l} \ . \tag{2.2}$$

We consider the electron and muon charge asymmetry with the kinematical cuts applied by the ATLAS Collaboration [23]. The events are required to have a missing transverse momentum $p_T^\nu > 25$ GeV and a transverse mass $M_T > 40$ GeV. The charged lepton transverse momentum must be $p_T^l > 20$. In Fig. 1 we report the ATLAS data and we show the NNLO results using NNLO parton densities from the MSTW2008 [24] and NNPDF [25] Collaborations (with 3-loops α_S) and fixing the renormalization and factorization scales to the value $\mu_R = \mu_F = m_W$. The errors on the histograms correspond to an estimate of the numerical errors in the Monte Carlo integration. We see that the LHC data are already sufficiently accurate to distinguish among different PDFs sets.

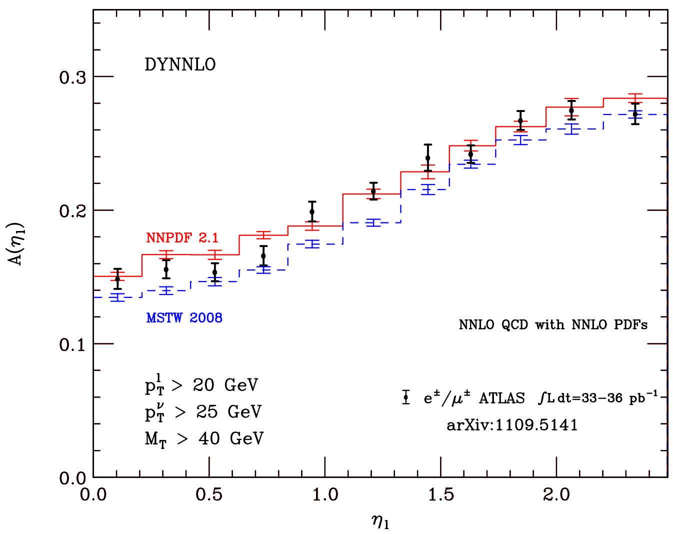

Figure 1: *Lepton charge asymmetry in NNLO QCD compared to ATLAS data [23].*

3. Associated W-Higgs production

We now consider the associated W-Higgs production in hadronic collisions. The NLO and the bulk of the NNLO QCD corrections for this process have the same structure of those for the vector boson production (with the Higgs boson radiated by the vector boson). The remaining NNLO contributions are mediated by a heavy-quark (mainly top) loop. These corrections were recently

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computed for the total cross section in Ref. [12]: their effect over the NNLO cross section for $m_H \sim 120$ GeV is at the level of about 1% for the LHC and less than 1% for the Tevatron [1].

Starting from the NNLO QCD calculation for the DY process [5], we were able to compute the DY-like NNLO corrections for the associated WH production which were encoded in an extended version of the numerical program `DYNNLO` [26]. We included finite-width effects, the leptonic decay of the W boson, with its spin correlations, and the decay of the Higgs boson into a $b\bar{b}$ pair.

We now present a selection of numerical results. We consider a SM Higgs boson with mass $m_H = 120$ GeV and width $\Gamma_H = 3.47$ MeV [27]. The $H \to b\bar{b}$ decay is computed at tree level in the massless approximation and the $Hb\bar{b}$ Yukawa coupling is normalized such that $BR(H \to b\bar{b}) = 0.649$ [27]. We use the MSTW2008 [24] sets of PDFs at the corresponding perturbative order (LO, NLO and NNLO with 1, 2 and 3-loops α_S) and we fix the renormalization and factorization scales to the value $\mu_R = \mu_F = m_W + m_H$.

We start by considering WH production at the LHC at $\sqrt{s} = 7$ TeV and we use the following cuts (see Ref. [28]). We require the charged lepton to have transverse momentum $p_T^l > 30$ GeV and pseudorapidity $|\eta_l| < 2.4$. Jets are reconstructed with the *anti-k_T* algorithm with $R = 0.5$ [29]. We require exactly two b-jets with $p_T > 20$ GeV and $|\eta_l| < 2.4$. Finally there should not be other jets with $p_T > 20$ GeV and $|\eta| < 2.5$. In Fig. 2 we show the transverse-momentum spectrum of the Higgs at NLO and NNLO, with and without the jet veto condition. We see that when a veto on additional jets is applied, the impact of the QCD corrections is more sizable and the stability of the fixed-order calculation is challenged [26].

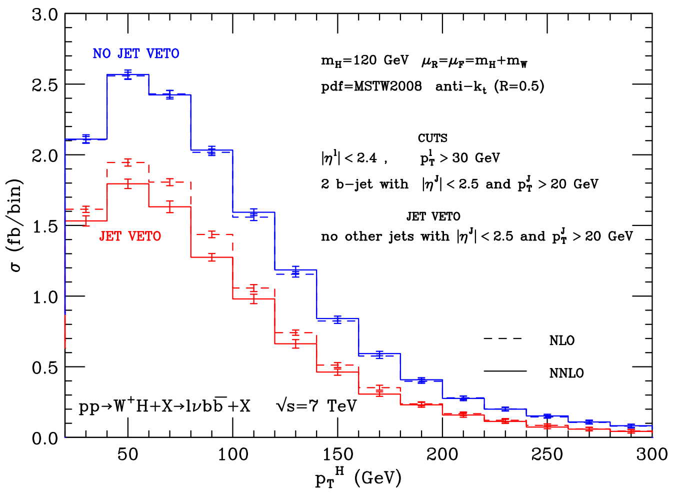

Figure 2: *Transverse-momentum spectrum of the Higgs boson for $pp \to W^+H + X \to l\nu b\bar{b} + X$ at the LHC at $\sqrt{s} = 7$ TeV, with (red histograms) and without (blue histograms) the jet veto condition at NLO (dashes) and NNLO (solid).*

We now turn to consider WH production at the Tevatron ($p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV). We use the following selection cuts (see e.g. Ref. [30]). We require the charged lepton to have transverse momentum $p_T^l > 20$ GeV and pseudorapidity $|\eta_l| < 2$, and the missing transverse momentum

[1] In the case of the associated Z-Higgs production, there is a set of NNLO contribution, induced by gluons and mediated by heavy-quark loops, which have a sizable contribution at the 5% level [11, 13].

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of the event to fulfil $p_T^{\rm miss} > 20$ GeV. Jets are reconstructed with the k_T algorithm with $R = 0.4$ [31]. We require exactly two jets with $p_T > 20$ GeV and $|\eta| < 2$, and at least one of them has to be a b jet, with $|\eta| < 1$.

In Fig. 3 we show the transverse-momentum spectrum of the dijet system at LO, NLO and NNLO. The lower panel of the figure shows the ratio NNLO/NLO. We see that the shape of the spectrum is rather stable, when going from NLO to NNLO, within the statistical uncertainties of the Monte Carlo numerical integration, showing a very good stability of the perturbative expansion.

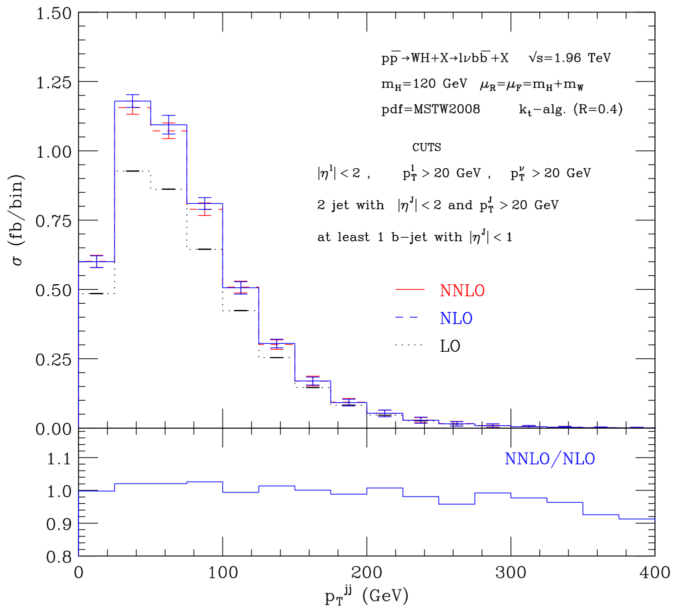

Figure 3: *Transverse-momentum spectrum of the dijet system for $p\bar{p} \to WH + X \to l\nu b\bar{b} + X$ at the Tevatron at LO (dots), NLO (dashes) and NNLO (solid).*

4. Conclusions

We have illustrated two calculations of the NNLO QCD corrections for vector boson production and for WH production in hadronic collisions. Both calculations are implemented in parton level Monte Carlo programs that allow the user to apply arbitrary kinematical cuts on the final state leptons and on the accompanying jet activity. We have shown results for the lepton charge asymmetry in NNLO QCD taking into account the lepton kinematical cuts that are applied by the ATLAS Collaboration at the LHC.

For the associated WH production, we have studied the impact of the NNLO QCD corrections for two typical distribution at the Tevatron and the LHC. At the Tevatron, the perturbative expansion appears under good control. At the LHC, by following the selection strategy of CMS, we have found that when a veto on additional jets is applied, the impact of QCD corrections is more sizable.

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