W+n-Jet Predictions at the Large Hadron Collider at Next-To-Leading Order Matched with a Parton Shower

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W+n-jet predictions at the Large Hadron Collider at next-to-leading order matched with a parton shower

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For the first time, differential cross sections for the production of W-bosons in conjunction with up to three jets, computed at next-to leading order in QCD and including parton shower corrections, are presented and compared to recent experimental data from the Large Hadron Collider.

A thorough understanding of the production of an electroweak gauge boson in association with multiple jets is central to the experimental physics program at the Large Hadron Collider (LHC). Such events are abundant and constitute an important background to many new physics searches [1]. They typically involve multiple kinematic scales and exhibit polarization phenomena [2]. Their study is vital to improve the understanding of quantum chromodynamics (QCD) in hadron-collider environments [3, 4], to measure the collider luminosity, to determine the jet energy scale and to study multiple parton scattering processes [5]. The most copious event rates occur when the gauge boson is a W. Predicting W+jet production with the most precise theoretical tools is therefore of paramount importance for the continued success of the LHC physics program.

Typically, good agreement is found when comparing W+jets experimental data with perturbative calculations performed at next-to-leading order (NLO) in QCD. Corresponding theoretical predictions have recently been made for associated production with three and even four jets [6–8]. Despite their continued success, such calculations suffer from logarithmic corrections due to intra-jet parton evolution, and from the fact that they are performed at the parton level. The latter makes them unsuitable for direct use in a detector simulation, and requires additional nonperturbative corrections before a comparison to data can be performed. The Mc@Nlo [9] and Powheg [10] methods remedy this situation by matching NLO QCD matrix elements with the resummation encoded in the parton showers of general-purpose Monte-Carlo event generators [11], allowing one to obtain well-understood hadron-level results at NLO accuracy. Results obtained with these two techniques include Z+1-jet production [12], W+2-jets production [13] and dijet production [14].

In this letter we present a new automated approach to matching NLO results to parton showers. Our method is a variant of the Mc@Nlo algorithm [15] but handles the soft behavior of matrix elements exactly, for processes with arbitrarily complex color configurations. We have validated the method for the W+jets processes. Using this technique, it is now possible, for the first time, to perform a matching of matrix elements and parton showers for W production in association with up to three jets at NLO accuracy. This process includes the most general color topologies, allowing us to demonstrate that the approach is universal, and permitting its future extension to other processes with similar or even higher final-state multiplicities.

Our new scheme to implement the Mc@Nlo technique is based on the exact exponentiation of Catani-Seymour dipole subtraction terms [15]. This method allows to circumvent the otherwise occurring integral over residual real-radiative contributions to the NLO cross section, that arise from the modified subtraction scheme in Mc@Nlo [9]. It also allows, for the first time, to obtain the correct soft-gluon limit in the first emission of the parton shower, such that no ad-hoc adjustments to the splitting kernels must be made. In fact our approach can be shown to correctly take into account the full color structure of the processes at NLO and in particular to correctly reproduce the soft gluon limit.

The Mc@Nlo cross section can be written as [9, 15]

$$\begin{aligned}\sigma \;=\; &\int \mathrm{d}\Phi_B\,\bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B)\left[\,\bar{\Delta}^{(\mathrm{A})}(t_0)\right.\\ &\qquad\left.+\int_{t_0}\mathrm{d}\Phi_1\frac{\mathrm{D}^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\,\bar{\Delta}^{(\mathrm{A})}(t)\right]\\ &+\int \mathrm{d}\Phi_R\,\mathrm{H}^{(\mathrm{A})}(\Phi_R)\;,\end{aligned} \tag{1}$$

where

$$\begin{aligned}\bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B) \;=\; &\mathrm{B}(\Phi_B)+\tilde{\mathrm{V}}(\Phi_B)+\mathrm{I}^{(\mathrm{S})}(\Phi_B)\\ &+\int \mathrm{d}\Phi_1\left[\,\mathrm{D}^{(\mathrm{A})}(\Phi_B,\Phi_1)-\mathrm{D}^{(\mathrm{S})}(\Phi_B,\Phi_1)\right]\end{aligned} \tag{2}$$

The terms B, $\tilde{\mathrm{V}}$, $\mathrm{I}^{(\mathrm{S})}$, and $\mathrm{D}^{(\mathrm{S})}$ represent the Born contribution, virtual correction plus collinear counterterms, integrated subtraction terms and real subtraction terms. Φ_B and Φ_R denote Born- and real-emission phase space with $\Phi_R = \Phi_B \otimes \Phi_1$, where Φ_1 represents the phase space of the respective additional parton emission. Real-emission matrix elements R are separated into an infrared-singular (soft) and an infrared-regular (hard) part, $\mathrm{D}^{(\mathrm{A})}$ and $\mathrm{H}^{(\mathrm{A})}$, where $\mathrm{R} = \mathrm{D}^{(\mathrm{A})} + \mathrm{H}^{(\mathrm{A})}$. This leads to the definition of the Sudakov form factor

$$\bar{\Delta}^{(\mathrm{A})}(t,t') \;=\; \exp\left\{-\int_t^{t'} \mathrm{d}\Phi_1\,\frac{\mathrm{D}^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\right\}\,. \quad (3)$$

The key point of our new technique is that the integral in Eq. (2) is avoided, since in our approach $\mathrm{D}^{(\mathrm{A})} = \mathrm{D}^{(\mathrm{S})}$, i.e. the subtraction kernels are also employed for parton showering. This can be achieved using Catani-Seymour subtraction, by dynamically correcting a parton shower based on spin-and color-averaged splitting operators. The method was applied previously to the $W^\pm$-Z- and Higgs+1-jet production processes [15]. In this publication we show that it is not limited to the case of one final-state parton at Born level, with a relatively trivial colour structure. We present results for W+2- and W+3-jet production, which contain the most general non-trivial color structures.

We use the SHERPA event generator [16], including its automated MC@NLO implementation [15]. The finite part of virtual corrections is computed using the BLACKHAT library [7], the Born part and phase space integration is provided by the matrix-element generator AMEGIC++ [17], including an automated implementation [18] of the Catani-Seymour dipole subtraction method [19]. The parton shower model [20] uses transverse momentum as ordering parameter, thus avoiding the problem of truncated emissions [10]. We restrict the resummation region using the methods described in [21] by setting the resummation scale, μ_Q, identical to the factorization scale, μ_F. We analyze the dependence of our results on the resummation scale by varying it in the range $\sqrt{1/2}\mu_Q \ldots \sqrt{2}\mu_Q$. We compare this variation with the uncertainty of the NLO calculation that arises from varying renormalization and factorization scales in the range $1/2\mu_{R/F} \ldots 2\mu_{R/F}$ [8].

Note that for the W+3-jet virtual matrix element we use the leading-color approximation in BLACKHAT only, to avoid an unnecessary increase in CPU time for the simulation. Subleading color configurations in virtual corrections often play a minor role in W+multi-jet processes [22]. They might, however, be important in other situations. As we focus on the interface between the NLO calculation and the parton shower in fairly inclusive observables, sub-leading colour effects are neglected. The CTEQ6.6 PDF set [23] is employed together with the corresponding parametrization of the running coupling. Following [24] renormalization and factorization scales are chosen as $\mu_R = \mu_F = 1/2\,\hat{H}'_T$, where $\hat{H}'_T = \sqrt{\sum p_{T,j}^2 + E_{T,W}^2}$. Predictions are presented at two different levels of event simulation:

"NLO": Fixed-order matrix-element calculation,

"MC@NLO PL": MC@NLO including full parton showering, but no non-perturbative effects.

The aim of this study is to present and validate an application of the MC@NLO variant suggested in [15] to processes with complex QCD final states. Therefore, non-perturbative effects, stemming from hadronization, hadron decays or multiple parton interactions are neglected in this study[1]. The scale uncertainties of NLO results are quoted to gauge the resummation uncertainties from the MC@NLO.

The analysis is carried out with the help of Rivet [25] following a recent study of $W^\pm$+jets production by the ATLAS collaboration [4]. Events are selected to contain a lepton within $|\eta| < 2.5$ with $p_\perp > 20$ GeV and requiring $E_T^{\mathrm{miss}} > 25$ GeV. A cut on $m_{\mathrm{T}}^{\mathrm{W}} > 40$ GeV is additionally applied. All particles other than the leading electron and neutrino are clustered into anti-k_t jets with $R = 0.4$ and $p_\perp > 30$ GeV. The analysis is carried out in jet multiplicity bins up to $N = 3$ and cross sections are studied differentially in several observables.

The results for each observable are predicted at NLO accuracy, i. e. all differential cross sections for $W^\pm + \geq n$-jet events are generated using the $W^\pm + n$-jet NLO or MC@NLO calculation. For $n > 0$, the W+n-jet matrix element must be regularized by requiring at least n jets with a minimum transverse momentum. This cut is chosen to be $p_\perp^{\mathrm{gen}} > 10$ GeV to make the event sample inclusive enough for the analysis. We have checked that our results are independent of the precise value of this cut by varying it from 5 to 15 GeV in every individual jet bin.

Table I compares total cross sections in four inclusive jet multiplicity bins. The ATLAS measurement is reproduced very well both by the fixed order calculation as well as by the MC@NLO matched simulation. The agreement between the NLO results and the MC@NLO simulation is excellent, indicating that the matching to the parton shower does not alter the jet production rate as predicted by the fixed-order calculation.

In Fig. 1 we display a comparison of the transverse momentum spectra of the first, second and third hardest jet in $W+\geq$ 1-, 2- and 3-jet production. No significant changes are observed when switching from the fixed-order calculation to the MC@NLO simulation, again indicating that the hard kinematics predicted by the NLO result are respected in the subsequent parton-shower evolution.

Fig. 2 focuses on $W+\geq$ 2-jet events. Angular correlations between the two leading jets are sensitive to QCD

[1] The observables displayed here are relatively insensitive to non-perturbative corrections and have been analyzed in detail in [15].

$W^{\pm}+\geq n$ jets	ATLAS	NLO	MC@NLO 1em	MC@NLO PL
$n=0$	5.2 ± 0.2	5.06(1)	5.09(3)	5.06(3)
$n=1$, $p_{\perp\,j}>20$ GeV	0.95 ± 0.10	0.958(5)	0.968(10)	0.889(10)
$p_{\perp\,j}>30$ GeV	0.54 ± 0.05	0.527(4)	0.534(7)	0.474(7)
$n=2$, $p_{\perp\,j}>20$ GeV	0.26 ± 0.04	0.263(2)	0.260(5)	0.236(4)
$p_{\perp\,j}>30$ GeV	0.12 ± 0.02	0.120(1)	0.123(2)	0.109(2)
$n=3$, $p_{\perp\,j}>20$ GeV	0.068 ± 0.014	0.072(3)	0.059(3)	0.060(3)
$p_{\perp\,j}>30$ GeV	0.026 ± 0.005	0.026(1)	0.022(2)	0.021(1)

TABLE I. Total cross sections in nb for $W^{\pm}+\geq 0,1,2,3$ jet production as measured by ATLAS [4] compared to predictions from the corresponding fixed order calculations, and matrix-element/shower level MC@NLO simulations. Statistical uncertainties of the theoretical predictions are quoted in parentheses.

corrections in the $W+2$-jet process and are thus a useful observable to validate the QCD radiation pattern which is generated in our MC@NLO. Both, the rapidity and azimuthal separation of the jets are predicted in perfect agreement with data.

In summary, we have shown in this letter how our recently proposed method for implementing MC@NLO can be used to produce novel and relevant results for one of the most challenging collider signatures to date. We have compared results for W+0-, 1-, 2- and 3-jet production to recent ATLAS data and found excellent agreement for all observables, with only a selection of them presented here. In so doing, for the first time results for W+3-jets production were presented. The success and the simplicity of our MC@NLO variant make it a prime candidate for the implementation of a matrix-element parton-shower merging algorithm at next-to-leading order.

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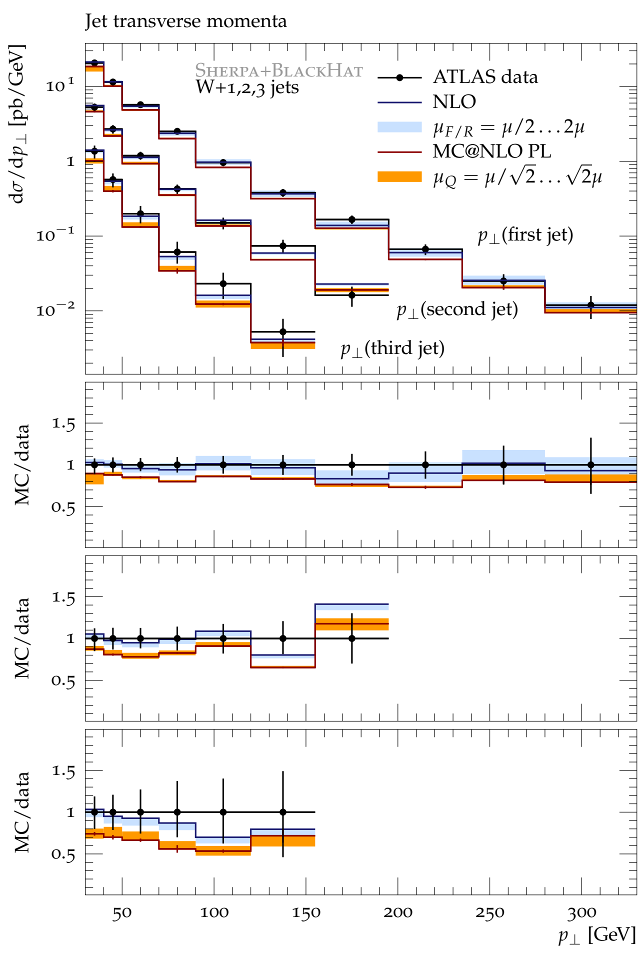

FIG. 1. Transverse momentum of the first, second and third jet (from top to bottom) in $W^{\pm}+\geq 1,2,3$ jet production as measured by ATLAS [4] compared to predictions from the corresponding fixed order and MC@NLO simulations. The blue band display fixed-order uncertainties, the orange band shows resummation uncertainties.

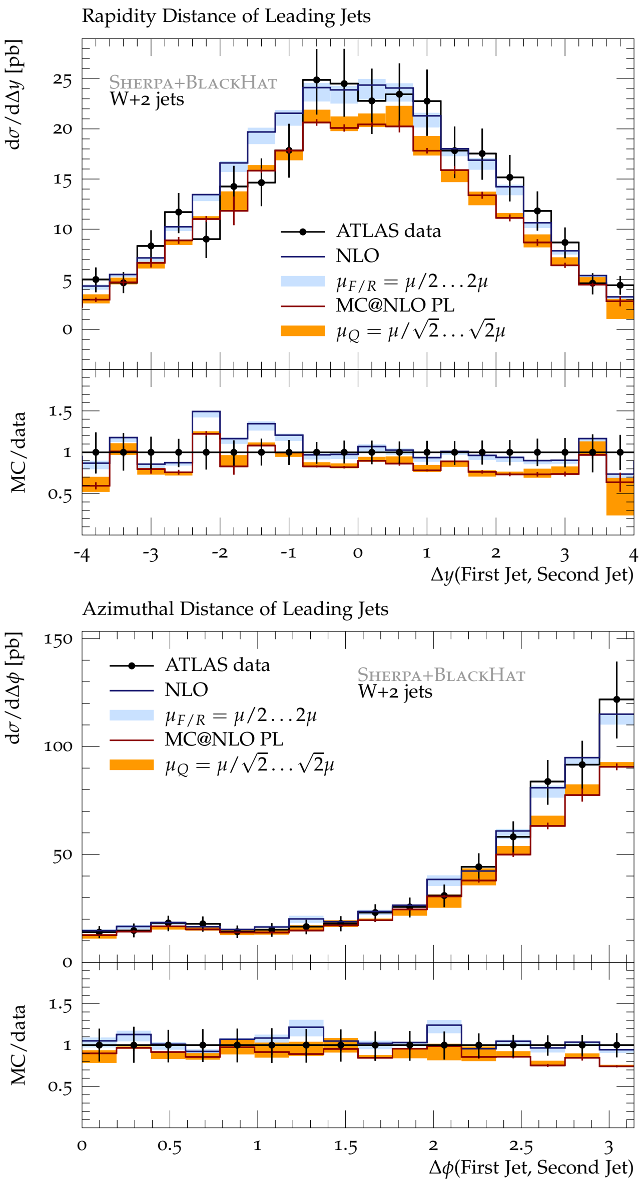

FIG. 2. Angular correlations of the two leading jets in $W^{\pm}+ \geq 2$ jet production as measured by ATLAS [4] compared to predictions from the $W^{\pm} + 2$ jet fixed order and Mc@Nlo simulations. The blue band display fixed-order uncertainties, the orange band shows resummation uncertainties.

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