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$W+n$-jet predictions with Mc@Nlo in Sherpa

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Results for the production of W-bosons in conjunction with up to three jets including parton shower corrections are presented and compared to recent LHC data. These results consistently incorporate the full next-to leading order QCD corrections through the Mc@Nlo method, as implemented in the Sherpa event generator, with the virtual corrections obtained from the BlackHat library.

The production of W-bosons accompanied with QCD jets is a Standard-Model reaction central to the experimental program at the LHC, as it constitutes an important background to many new physics searches. It is also of interest in its own right, to study jet production and evolution in a hadron-collider environment [1, 2], to improve the jet energy scale determination by the experiments, or to study multiple parton scattering processes. At the LHC as well as at the Tevatron, typically, good agreement is found when comparing respective data with next-to-leading order (NLO) perturbative QCD predictions, which have recently been made for W-boson production in association with three and even four jets [3–5].

The development of two methods to match NLO matrix elements with parton showers, Mc@Nlo [6] and Powheg [7], allowed, at the same time, to include earlier parton-level calculations into parton-shower Monte-Carlo (PSMC) programs, among others this includes Z+1-jet production in the PowhegBox [8] and W+2-jets production in aMc@Nlo [9]. In this letter we present the implementation of the W+jets process in a variant of the Mc@Nlo method [10], including up to three jets at NLO accuracy. Our implementation in Sherpa [11] can easily be extended to other processes with similar or even higher final state multiplicities. For the process at hand, we use the BlackHat library for NLO calculations to evaluate the finite part of virtual corrections [4].

Our new scheme to implement the Mc@Nlo technique is based on the exact exponentiation of Catani-Seymour dipole subtraction terms [10]. 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 [6]. It also allows, for the first time, to obtain the correct soft-gluon limit in the first emission of the PSMC, such that no adjustments to the splitting kernels of the parton shower must be made in the soft region to match the correct behavior of the subtraction terms. Due to the existence of multiple color structures at Born level, this point is particularly important when simulating processes with Mc@Nlo techniques that involve a large number of QCD partons, like W+3 jets. Our method allows to prove that the approximations which are usually made in Mc@Nlo to deal with soft divergences are justified. In fact it can be shown to correctly take into account the full color structure of the processes at NLO.

The Mc@Nlo cross section can be written in the form [6, 10]

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

where

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

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 $\Phi_R = \Phi_B \otimes \Phi_1$. Real-emission matrix elements R are separated into an infrared-singular (soft) and an infrared-regular (hard) part, $\mathrm{D}^{(\mathrm{A})}$ and $\mathrm{H}^{(\mathrm{A})}$ as $\mathrm{R} = \mathrm{D}^{(\mathrm{A})} + \mathrm{H}^{(\mathrm{A})}$. This leads to the definition of the Sudakov form factor

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

The key point of our new technique is that the integral in Eq. (2) is avoided if $\mathrm{D}^{(\mathrm{A})} = \mathrm{D}^{(\mathrm{S})}$, i.e. if the subtraction kernels are employed for parton showering. This can be achieved using Catani-Seymour subtraction, by

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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 [10]. In this publication we show that it is not limited to the case of one final-state parton at Born level. We present results for W+2- and W+3-jet production, which contain the most general color structures. The latter of these two processes has neither been implemented in the MC@NLO nor in the POWHEG technique so far.

We use the framework of the SHERPA event generator [11], including its automated MC@NLO implementation [10], the matrix-element generator AMEGIC++ [12], an automated implementation [13] of the Catani-Seymour dipole subtraction method [14] and the parton shower model described in [15]. This parton shower uses transverse momentum ordering. We thus avoid the problem of truncated emissions [7]. We restrict the resummation region as described in [10] by setting $\alpha = 0.01$. We appreciate that this is a process-dependent parameter, which in the future is going to be replaced by a phase-space cut in terms of transverse momentum. Such a choice is physically more sound and will ultimately allow for a fully automated implementation which correctly resums all leading logarithms. The finite part of virtual corrections is computed using the BLACKHAT library [4]. For the W+3-jet virtual matrix element we use the leading-color approximation in BLACKHAT 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 [16]. They might, however, be important in other situations. As we focus on the interface between the NLO calculation and the parton shower in this publication these effects are neglected. The CTEQ6.6 PDF set [17] is employed together with the corresponding parametrization of the running coupling. Following [18] renormalization and factorization scales are chosen as $\mu_R = \mu_F = 1/2\,\hat{H}'_T$, where $\hat{H}'_T = \sqrt{\sum p^2_{T,j} + E^2_{T,W}}$. Predictions are presented at three different levels of event simulation:

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

"MC@NLO 1em": MC@NLO including only the first (hardest) emission in the parton shower,

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

Non-perturbative effects are neglected in this study[1] in order to focus on the features of the MC@NLO method in processes with intricate color topologies. The effects of multiple parton interactions, hadronization, hadron decays and final state QED radiation have been analyzed in detail in [10]. Likewise we do not quote scale uncertainties of the NLO results. Those have been analyzed in great detail in [5] and [10]. The aim of this study is instead to present an application of the MC@NLO variant suggested in [10] to complex QCD final states in order to verify its universality and test its versatility.

The analysis is carried out with the help of Rivet [19] following a recent study of $W^{\pm}$+jets production by the ATLAS collaboration [2]. Events are selected to contain a lepton within $|\eta| < 2.5$ with $p_\perp > 20$ GeV and requiring $E_T^{\rm miss} > 25$ GeV. A cut on $m_{\rm T}^{\rm W} > 40$ 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 $p_\perp^{\rm gen} > 10$ 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 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 with the help of Catani-Seymour subtraction and a parton shower based on Catani-Seymour subtraction kernels can be used to produce novel and relevant results for one of the most challenging collider signatures to date. Pre-

[1] The observables displayed here are relatively insensitive to non-perturbative corrections.

$W^{\pm}+\geq n$ 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 [2] 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.

dictions for W+3-jets production were made, a process which has not been attempted in either the POWHEG or the MC@NLO framework so far. 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. 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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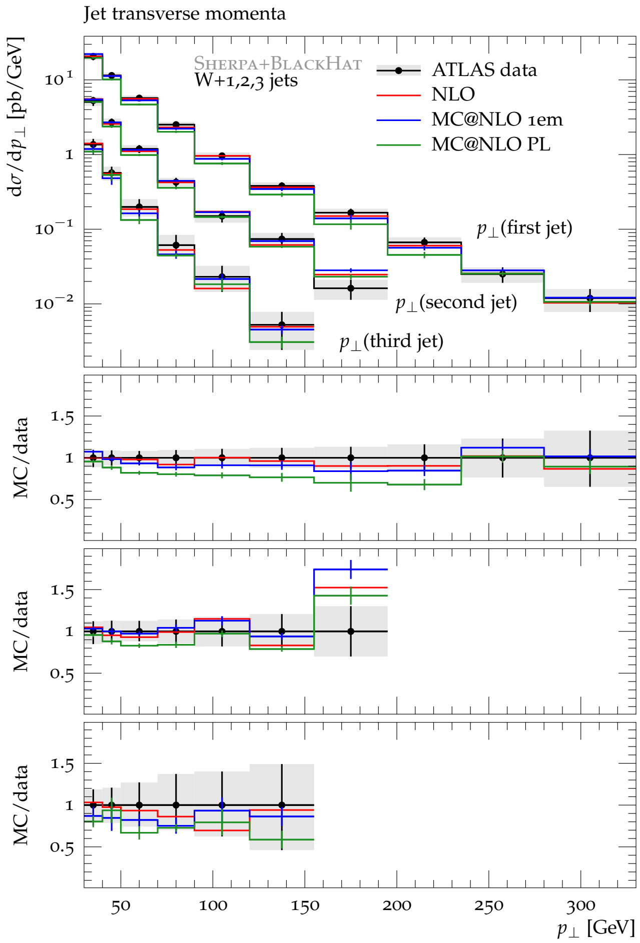

FIG. 1. Transverse momentum of the first, second and third jet (from top to bottom) in $W^\pm + \geq 1, 2, 3$ jet production as measured by ATLAS [2] compared to predictions from the corresponding fixed order and Mc@Nlo simulations. The gray bands display the combined statistical and systematic experimental uncertainties.

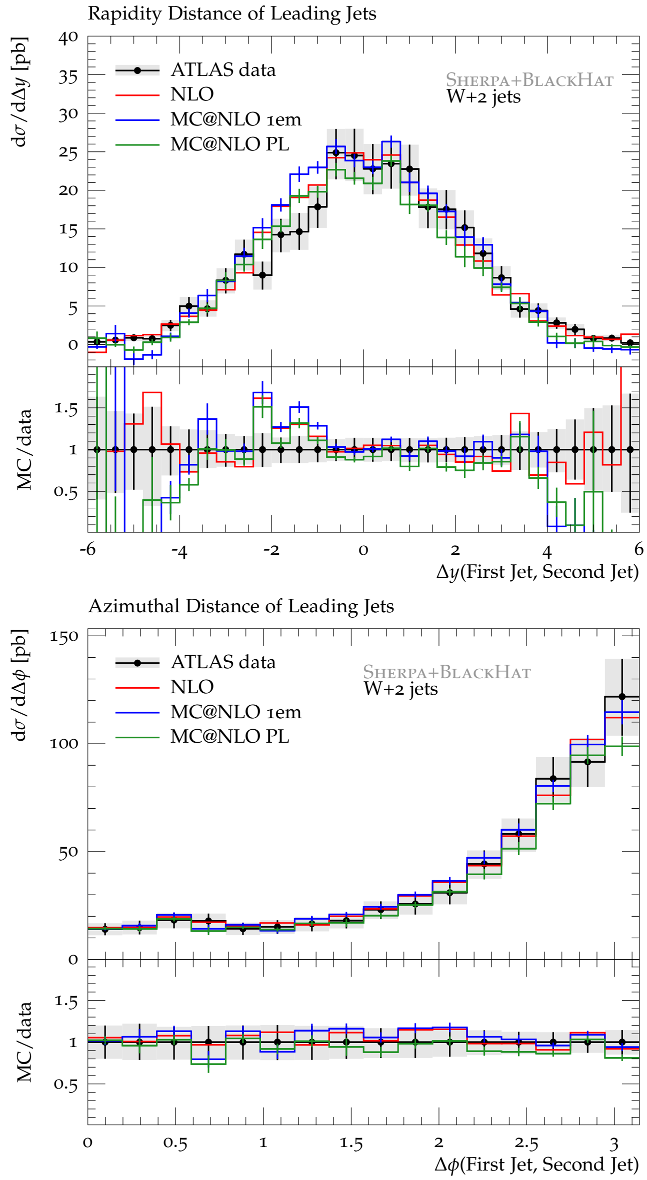

FIG. 2. Angular correlations of the two leading jets in $W^\pm + \geq 2$ jet production as measured by ATLAS [2] compared to predictions from the $W^\pm + 2$ jet fixed order and Mc@Nlo simulations. The gray bands display the combined statistical and systematic experimental uncertainties.