Nonperturbative corrections and showering in NLO-matched event generators [a]

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We study contributions from nonperturbative effects and parton showering in NLO event generators, and present applications to jet final states. We find p_T-dependent and rapidity-dependent corrections which can affect the shape of observed jet distributions at the LHC. We illustrate numerically the kinematic shifts in longitudinal momentum distributions from the implementation of energy-momentum conservation in collinear shower algorithms.

Monte Carlo event generators are used in analyses of complex final states at the Large Hadron Collider (LHC) [1] both to supplement finite-order perturbative calculations with all-order QCD radiative terms, encoded by parton showers, and to incorporate nonperturbative effects from hadronization, multiple parton interactions, underlying events [2,3]. In this article we report results from our study [4] of nonperturbative (NP) and parton-showering (PS) corrections in the context of matched NLO-shower Monte Carlo generators. The results we present refer to jet final states. Further results for massive states may be found in [4].

LHC experiments have measured inclusive jet production [5,6] over a kinematic range in transverse momentum and rapidity much larger than in any previous collider experiment. Baseline comparisons with Standard Model theoretical predictions are based either on next-to-leading-order (NLO) QCD calculations, supplemented with nonperturbative (NP) corrections estimated from Monte Carlo event generators [5,6], or on NLO-matched parton shower event generators [7]. The first kind of comparison shows that the NLO calculation agrees with data at central rapidities, while increasing deviations are seen with increasing rapidity at large transverse momentum p_T [5]. The question arises of whether such behavior is associated with higher-order perturbative contributions or with nonperturbative components of the cross section. The second kind of comparison, based on POWHEG calculations [8] in which NLO matrix elements are matched with parton showers [2,3], improves the description of data, indicating that higher-order radiative contributions taken into account via parton showers are numerically important. At the same time, the results show large differences between POWHEG calculations interfaced with different shower generators, PYTHIA [2] and HERWIG [3], in the forward rapidity region, pointing to enhanced sensitivity to details of the showering.

NP correction factors are obtained in [5,6] by using leading-order Monte Carlo (LO-MC) generators [2,3]. The method to determine these factors is to compare a Monte Carlo simulation including parton showers, multiparton interactions and hadronization, and a Monte Carlo simulation including only parton showers in addition to the LO hard process. While this is a natural way to estimate NP corrections from LO+PS event generators, it is noted in [4] that when these

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corrections are combined with NLO parton-level results a potential inconsistency arises because the radiative correction from the first gluon emission is treated at different levels of accuracy in the two parts of the calculation. To avoid this, Ref.[4] proposes a method which uses NLO Monte Carlo (NLO-MC) generators to determine the correction. In this case one can consistently assign correction factors to be applied to NLO calculations. This method allows one to study separately correction factors to the fixed-order calculation due to parton showering effects. To do this, Ref.[4] introduces the nonperturbative (NP) and showering (PS) correction factors, K^{NP} and K^{PS}, as

$$K^{NP} = N_{NLO-MC}^{(ps+mpi+had)} / N_{NLO-MC}^{(ps)} \ , \tag{1}$$

$$K^{PS} = N_{NLO-MC}^{(ps)} / N_{NLO-MC}^{(0)} \ , \tag{2}$$

where $(ps + mpi + had)$ denotes a simulation including parton showers, multiparton interactions and hadronization, while (ps) denotes a simulation including parton showers only. The denominator in Eq. (2) is defined by switching off all components beyond NLO in the Monte Carlo simulation.

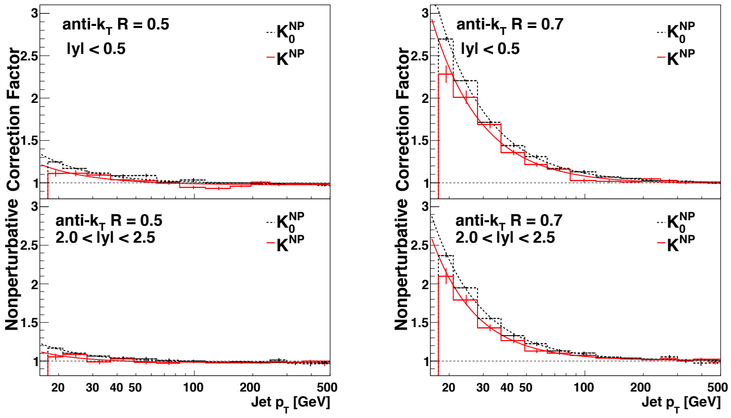

Figure 1: *The NP correction factors to jet transverse momentum distributions obtained using* Pythia *and* Powheg *respectively, for* $|y| < 0.5$ *and* $2 < |y| < 2.5$*. Left:* $R = 0.5$*; Right:* $R = 0.7$*.*

The factor K^{NP} in Eq. (1) differs from the LO-MC NP factor [5,6] because of the different definition of the hard process. In particular the multi-parton interaction p$_T$ cut-off scale is different in the LO and NLO cases. Numerical results are shown in Fig. 1. The factor K^{PS} in Eq. (2), on the other hand, is new. It singles out contributions due to parton showering and has not been considered in previous analyses. Unlike the NP correction, it gives in general finite effects also at large p$_T$. Results are plotted in Fig. 2, showing that this correction is y and p$_T$ dependent, especially when rapidity is non-central, so that it cannot be treated as a rescaling.

The correction factor in Fig. 2 comes from initial-state and final-state showers. These are interrelated so that the combined effect is nontrivial and is not obtained by simply adding the two[4]. The effect from parton shower is largest at large $|y|$, where the initial-state parton shower is mainly contributing at low p_T, while the final-state parton shower is contributing significantly over the whole p_T range.

The main effect of initial-state showering is associated with the kinematic shifts in longitudinal momentum distributions first noted in[9]. These shifts result, quite generally, from combining the approximation of collinear, on-shell partons with the requirements of energy-momentum conservation in the Monte Carlo generator. More precisely, the Monte Carlo first generates hard subprocess events in which the momenta k_j of the partons initiating the hard scatter are on shell, and are taken to be fully collinear with the incoming state momenta. Next the showering

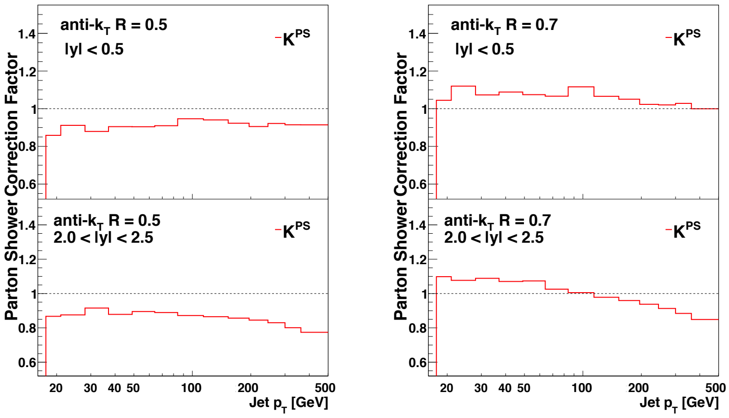

Figure 2: *The parton shower correction factor to jet transverse momentum distributions, obtained from Eq. (2) using* Powheg *for* $|y| < 0.5$ *and* $2 < |y| < 2.5$*. Left:* $R = 0.5$*; Right:* $R = 0.7$*.*

algorithm is applied, and complete final states are generated including additional QCD radiation from the initial and final parton cascades. As a result of QCD showering, the momenta k_j are no longer exactly collinear. Their transverse momentum is to be compensated by a change in the kinematics of the hard scattering subprocess. By energy-momentum conservation, however, this implies a reshuffling, event by event, in the fractions x_j of longitudinal momentum carried by the partons scattering off each other in the hard subprocess.

The size of the shift is illustrated in Fig. 3 [4] for the case of jets produced at different rapidities, by comparing the distribution in the parton longitudinal momentum fraction x before parton showering and after parton showering. We see that the longitudinal shift is negligible for central rapidities but becomes significant for $y > 1.5$. It characterizes the highly asymmetric parton kinematics [11] which becomes important for the first time at the LHC in significant regions of phase space. Although Fig. 3 is obtained using a particular NLO-shower matching scheme (Powheg), the effect is common to any calculation matching NLO with collinear showers. On the other hand, this is avoided in shower algorithms using transverse momentum dependent parton distributions [12,13,14,15] from the beginning, as for instance in [16,17].

In summary, the nonperturbative correction factor K^{NP} introduced from NLO-MC in Eq. (1) gives non-negligible differences compared to the LO-MC contribution [5,6] at low to intermediate jet p_T, while the showering correction factor K^{PS} of Eq. (2) gives significant effects over the whole p_T range and is largest at large jet rapidities y. Because of this y and p_T dependence, taking properly into account NP and showering correction factors changes the shape of jet distributions, and may thus influence the comparison of theory predictions with experimental data. Besides jets, longitudinal momentum shifts as in Fig. 3 also affect massive final states [4] such as Drell-Yan Z/W production. We anticipate that the showering correction factors will be relevant in particular in fits for parton distribution functions using inclusive jet and vector boson data.

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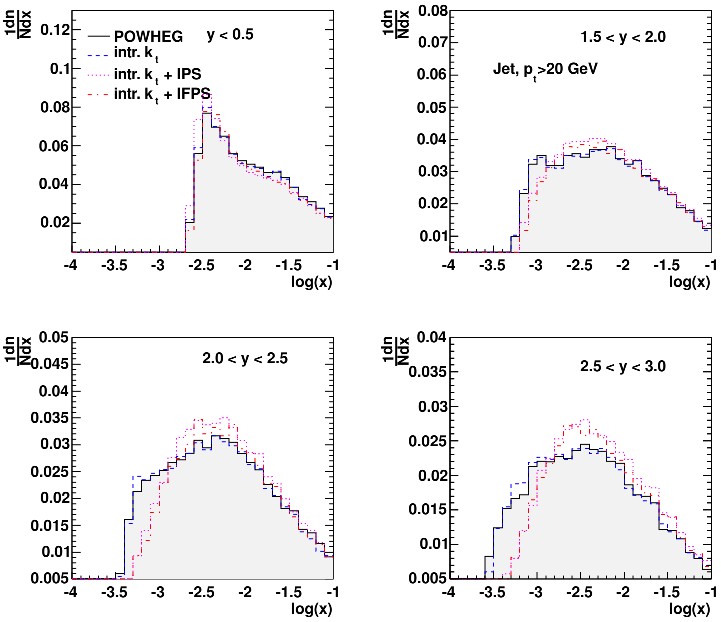

Figure 3: *Distributions in the parton longitudinal momentum fraction x before (POWHEG) and after parton showering (POWHEG+PS), for inclusive jet production at different rapidities for jets with $p_T > 18$ GeV obtained by the anti-kt jet algorithm with $R = 0.5$. Shown is the effect of intrinsic k_t, initial (IPS) and initial+final state (IFPS) parton shower.*

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