Nonperturbative corrections and showering in NLO-matched event generators

S. Dooling\textsuperscript{1}, P. Gunnellini\textsuperscript{3}, F. Hautmann\textsuperscript{2,3} and H. Jung\textsuperscript{1,4}

\textsuperscript{1}Deutsches Elektronen Synchrotron, D-22603 Hamburg
\textsuperscript{2}Theoretical Physics Department, University of Oxford, Oxford OX1 3NP
\textsuperscript{3}Physics and Astronomy, University of Sussex, Brighton BN1 9QH
\textsuperscript{4}Elementaire Deeltjes Fysica, Universiteit Antwerpen, B 2020 Antwerpen

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.

Monte Carlo event generators are used in analyses of complex final states at the Large Hadron Collider (LHC)\textsuperscript{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\textsuperscript{2,3}. In this article we report results from our study\textsuperscript{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\textsuperscript{4}.

LHC experiments have measured inclusive jet production\textsuperscript{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\textsuperscript{5,6}, or on NLO-matched parton shower event generators\textsuperscript{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 $p_T$\textsuperscript{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\textsuperscript{8} in which NLO matrix elements are matched with parton showers\textsuperscript{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\textsuperscript{2} and HERWIG\textsuperscript{3}, in the forward rapidity region, pointing to enhanced sensitivity to details of the showering.

NP correction factors are obtained in\textsuperscript{5,6} by using leading-order Monte Carlo (LO-MC) generators\textsuperscript{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\textsuperscript{4} that when these

\textsuperscript{4}Contributed at the XLVIII Rencontres de Moriond, March 2013.
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.\textsuperscript{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.\textsuperscript{4}
introduces the nonperturbative (NP) and showering (PS) correction factors, $K^{\text{NP}}$ and $K^{\text{PS}}$, as
\begin{equation}
K^{\text{NP}} = N^{(ps+mpi+had)}_{\text{NLO-MC}} / N^{(ps)}_{\text{NLO-MC}},
\end{equation}
\begin{equation}
K^{\text{PS}} = N^{(ps)}_{\text{NLO-MC}} / N^{(0)}_{\text{NLO-MC}},
\end{equation}
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.

The factor $K^{\text{NP}}$ in Eq. (1) differs from the LO-MC NP factor\textsuperscript{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 $K^{\text{PS}}$ 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\textsuperscript{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\textsuperscript{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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{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: $R = 0.7$.}
\end{figure}
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 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 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 from the beginning, as for instance in.

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 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 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.

**Acknowledgments**

We are grateful to the Moriond organizers and staff for the invitation to an exciting conference, and to the Moriond participants for interesting discussions.
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.

References

1. See S. Höche, SLAC preprint SLAC-PUB-14498 (2011) for a recent review.
2. T. Sjöstrand, S. Mrenna and P. Skands, JHEP 0605 (2006) 026.
3. G. Corcella et al., JHEP 0101 (2001) 010 [arXiv:hep-ph/0011363]; G. Corcella et al., arXiv:hep-ph/0210213.
4. S. Dooling, P. Gunnellini, F. Hautmann and H. Jung, arXiv:1212.6164 [hep-ph].
5. ATLAS Coll. (G. Aad et al.), Phys. Rev. D 86 (2012) 014022.
6. CMS Coll. (S. Chatrchyan et al.), Phys. Rev. Lett. 107 (2011) 132001; arXiv:1212.6660 [hep-ex].
7. P. Nason and B.R. Webber, arXiv:1202.1251 [hep-ph].
8. S. Alioli et al., JHEP 1104 (2011) 081.
9. F. Hautmann and H. Jung, Eur. Phys. J. C 72 (2012) 2254.
10. M. Cacciari, G. Salam and G. Soyez, JHEP 0804 (2008) 063.
11. M. Deak et al., JHEP 0909 (2009) 121; arXiv:0908.1181; arXiv:1012.6037 [hep-ph]; Eur. Phys. J. C 72 (2012) 1982; arXiv:1206.7090 [hep-ph].
12. E. Avsar, arXiv:1203.1916 [hep-ph]; arXiv:1108.1181 [hep-ph].
13. F. Hautmann, Acta Phys. Polon. B 40 (2009) 2139; Phys. Lett. B 655 (2007) 26; F. Hautmann and H. Jung, arXiv:0712.0568 [hep-ph]; arXiv:0805.1049 [hep-ph]; arXiv:0808.0873.
14. P.J. Mulders, Pramana 72 (2009) 83; P.J. Mulders and T.C. Rogers, arXiv:1102.4569 [hep-ph].
15. F. Hautmann, M. Hentschinski and H. Jung, Nucl. Phys. B865 (2012) 54; arXiv:1205.6358 [hep-ph]; arXiv:1209.6305 [hep-ph].
16. H. Jung et al., Eur. Phys. J. C 70 (2010) 1237; arXiv:1206.1796 [hep-ph].
17. S. Jadach and M. Skrzypek, Acta Phys. Polon. B 40 (2009) 2071; S. Jadach, M. Jezabek, A. Kusina, W. Placzek and M. Skrzypek, arXiv:1209.4291 [hep-ph].