PROCEEDINGS OF SCIENCE

**IPPP/12/91, DCPT/12/182, LPN12-131, SLAC–PUB–15305**

# Systematic uncertainties in NLOPS matching

**Marek Schönherr**[*†]
*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*
*E-mail:* marek.schoenherr@durham.ac.uk

**Stefan Höche**
*SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*

**Frank Krauss**
*Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK*

**Frank Siegert**
*Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, D-79104 Freiburg, Germany*

The MC@NLO and MEPS@NLO methods, as implemenated in the Monte-Carlo event generator framework SHERPA, are used to estimate the perturbative and non-perturbative uncertainties in various processes such as dijet production and the production of a $W$ boson in association with (multiple) jets.

*36th International Conference on High Energy Physics,*
*July 4-11, 2012*
*Melbourne, Australia*

[*]Speaker.

[†]Supported by the by the Research Executive Agency (REA) of the European Union under the Grant Agreement number PITN-GA-2010-264564 (LHCPhenoNet).

Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

 

## 1. Introduction

Being largely stimulated by the need for higher precission of theoretical predictions in both Standard Model analyses and new physics searches at the LHC, the simulation of higher-order QCD corrections in Monte Carlo event generators has seen vast improvements in recent years. To this end, two lines of development have been followed. In the MEPS approach [1, 2, 3, 4, 5, 6] higher-order tree-level matrix elements of successive final state parton multiplicity are merged into an inclusive sample, offering both leading-order accuracy for the production of hard partons and retaining the overall resummation of scale hierarchies through the parton shower at the same time. On the other hand NLOPS approaches, introduced as either MC@NLO [7] or POWHEG [8, 9], work on a single parton multiplicity elevating its accuracy to next-to-leading order. Both methods have been shown to be automatable [10, 11] within the SHERPA event generator framework [12]. Thereafter, it was sought to recombine both lines of development. In a first step, called the MENLOPS prescription, the NLOPS and MEPS methods have been combined using the NLOPS' NLO accuracy for the inclusive process supplementing it with higher-order tree-level matrix elements in an MEPS fashion [13]. In second step multiple NLOPS processes of successive parton multiplicity are combined, elevating the accuracy of the MEPS method to next-to-leading order, dubbed MEPS@NLO [14, 15]. In the following both the NLOPS and MEPS@NLO methods are summarised. Particular emphasis is put on both methods' major accompishments with respect to standard leading order computations: its increased theoretical accuracy expressed through reduced perturbative uncertainties.

## 2. NLOPS matching

Following the notation of [11] a general NLO+PS matching can be cast in the form of the following master formula

$$\langle O\rangle = \int \mathrm{d}\Phi_B\; \bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B)\left[\Delta^{(\mathrm{A})}(t_0,\mu_Q^2)\,O(\Phi_B)+\sum_i\int_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\mathrm{D}_i^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\,\Delta^{(\mathrm{A})}(t,\mu_Q^2)\,O(\Phi_R)\right] + \int \mathrm{d}\Phi_R\;\mathrm{H}(\Phi_R)\,O(\Phi_R)\,. \tag{2.1}$$

Therein, the NLO-weighted normalisation of the resummed events is defined as

$$\bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B) = \mathrm{B}(\Phi_B)+\tilde{\mathrm{V}}(\Phi_B)+\mathrm{I}^{(\mathrm{A})}(\Phi_B)+\sum_i\int\mathrm{d}\Phi_1\left[\mathrm{D}_i^{(\mathrm{A})}\Theta(\mu_Q^2-t)-\mathrm{D}_i^{(\mathrm{S})}\right](\Phi_B,\Phi_1)\,. \tag{2.2}$$

$t=t(\Phi_1)$ identifies the infrared limits of the additional parton's phase space and serves as an ordering variable of the parton shower resummation. The resummation kernels are then defined by the auxiliary set of subtraction kernels $\mathrm{D}^{(\mathrm{A})}$, ensuring the correct behaviour in both the soft and the collinear limit of the emission of an extra parton, exhibiting full colour and spin correctness in the respective limits. They imply the modified Sudakov form factor

$$\Delta^{(\mathrm{A})}(t_0,t_1) = \exp\left[-\int_{t_0}^{t_1}\mathrm{d}\Phi_1\,\frac{\mathrm{D}_i^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\right]\,. \tag{2.3}$$

An upper scale $\mu_Q$ limits the region of resummation, i.e. the exponent of the Sudakov form factor vanishes at $t = \mu_Q$. This scale has been made accessible for the first time in the implementation of [11] and can thus be used to study the uncertaity related to its arbitrariness. The finite remainder of the real emission cross section is then embedded in the so-called hard events defined through

$$\mathrm{H}(\Phi_R) = \mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathrm{A})}(\Phi_R)\,. \tag{2.4}$$

Fig. 1 now shows an evaluation of the resummation scale uncertainty in various MC@NLO implementations for $pp \to W + n$ jets [19] and contrasts it with the renormalisation and factorisation scale uncertainties in a standard fixed-order next-to-leading order calculation. Fig. 2 details all sources

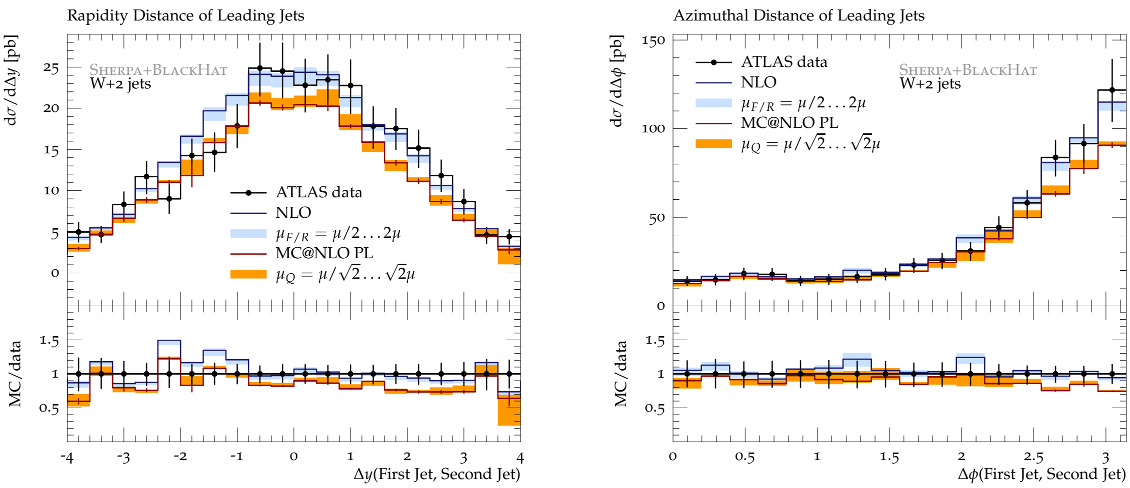


**Figure 1:** Rapidity (left) and azimuthal (right) separation of the two leading jet $pp \to \geq 2$ jets compared to ATLAS data [16].

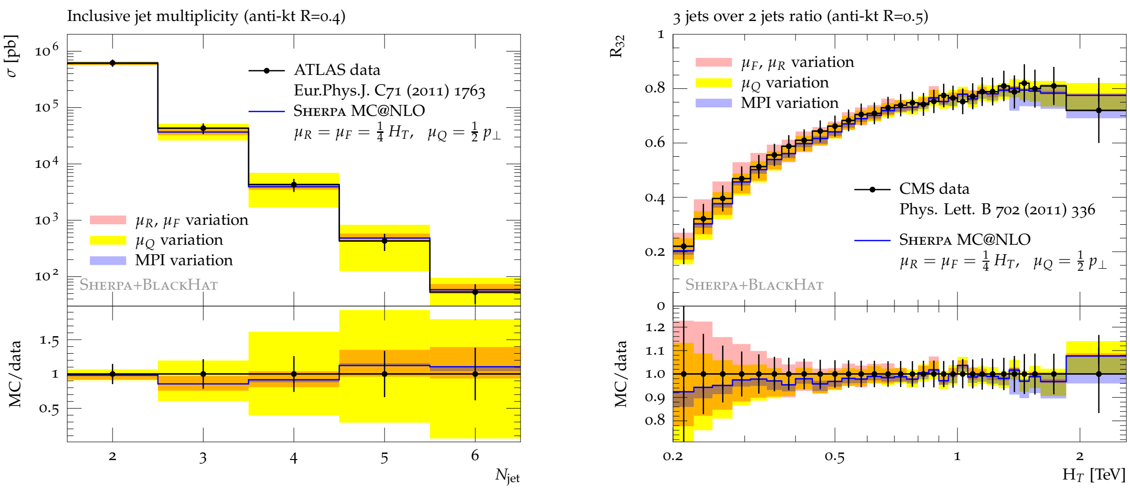


**Figure 2: Left:** Inclusive jet cross section in $pp \to \geq 2$ jets compared to ATLAS data [17]. **Right:** 3-jet over 2-jet ratio in dependence on the scalar transverse momentum sum of all jets in $pp \to \geq 2$ jets in comparison to CMS [18].

of perturbative ($\mu_R$, $\mu_F$, $\mu_Q$) as well as non-perturbative uncertainties due to the multiple interaction model in an MC@NLO implementation of inclusive and dijet production [20]. In all cases, the perturbative uncertainties for observables described at NLO accuracy are greatly reduced while the parton shower resummation provides the correct description when large hierarchies of scales in $t$ are present. At the same time, there are observables/regions where the uncertainty on the modelling of the soft structure of the event is non-negligible.

## 3. MEPS@NLO merging

The NLOPS matched calculations detailed in the previous section can now be used as input to extend the CKKW-type to next-to-leading order [15, 14]. The master formula for its construction reads as follows

$$\begin{aligned}
\langle O\rangle = & \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathrm{A})}\left[\Delta_n^{(\mathrm{A})}(t_c,\mu_Q^2)\, O_n + \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathrm{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_\mathrm{cut}-Q_{n+1})\, O_{n+1}\right] \\
& + \int \mathrm{d}\Phi_{n+1}\, \mathrm{H}_n^{(\mathrm{A})}\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q_\mathrm{cut}-Q_{n+1})\, O_{n+1} \\
& + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}\left(1+\frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}}\int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\right)\Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{n+1}-Q_\mathrm{cut}) \qquad (3.1)\\
& \qquad\qquad \times\left[\Delta_{n+1}^{(\mathrm{A})}(t_c,t_{n+1})\, O_{n+1} + \int_{t_c}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(\mathrm{A})}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathrm{A})}(t_{n+2},t_{n+1})\, O_{n+2}\right] \\
& + \int \mathrm{d}\Phi_{n+2}\, \mathrm{H}_{n+1}^{(\mathrm{A})}\, \Delta_{n+1}^{(\mathrm{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{n+1}-Q_\mathrm{cut})\, O_{n+2} + \ldots,
\end{aligned}$$

Therein an MC@NLO description of an $n$ parton multiplicity is restricted to have its emission produced at a jet measure $Q$ smaller than $Q_\mathrm{cut}$. The region with $Q > Q_\mathrm{cut}$ is then filled with an MC@NLO for the $n+1$ parton process. To restore the correct resummation with respect to the $n$ parton process to at least parton shower accuracy its Sudakov form factor $\Delta_n^{(\mathrm{PS})}$ is inserted. The overlap with similar terms in $\bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}$ is removed with the term in the braces on third line. A multijet merged description is then achieved by iteration eq. 3.1.

Again, the calculation benefits from the decreased theoretical uncertainty of its MC@NLO input processes. Figs. 3 and 4 exemplify this feature for the process $pp \to W+$ jets compared to ATLAS data. For this calculation the processes with 0, 1 and 2 additional jets are described at next-to-leading order while 3 and 4 addiotional jets have been merged on top of that at leading order accuracy. These different levels of accuracy can be directly seen in the respective uncertainties. Further, they are contrasted with a MENLOPS [13] prediction using an MC@NLO input only for the $pp \to W$ process and merging only leading order prediction for 1, 2, 3 and 4 additional jets on top.

## References

[1] S. Catani, F. Krauss, R. Kuhn and B. R. Webber, *QCD matrix elements + parton showers*, JHEP **11** (2001), 063, [hep-ph/0109231].

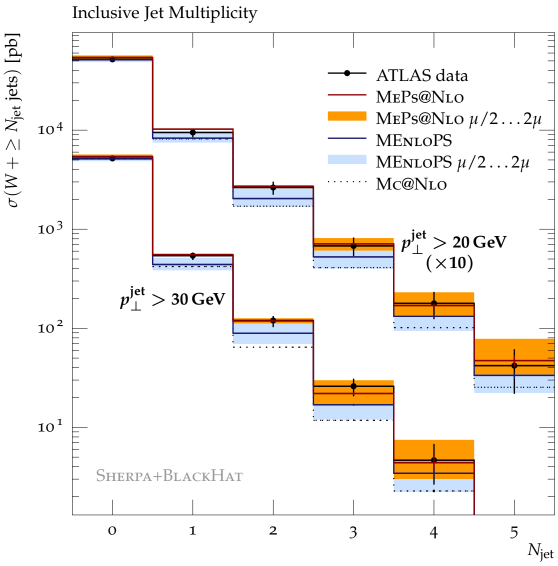


**Figure 3:** Cross section as a function of the inclusive jet multiplicity in $pp \to W+$jets events compared to ATLAS data [16].

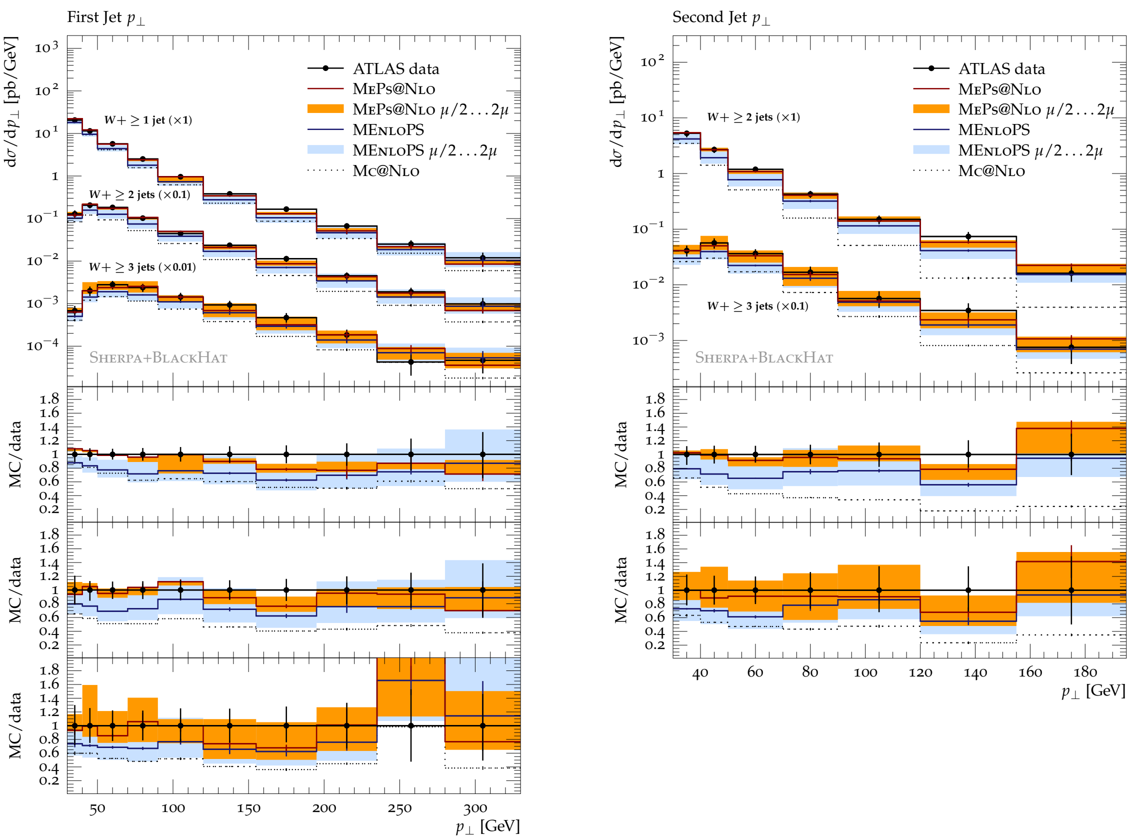


**Figure 4:** Differential cross section as a function of the transverse momentum of the first (left) and second (right) jet in $pp \to W+\geq 1,2,3\,$jets events compared to ATLAS data [16].

[2] L. Lönnblad, *Correcting the colour-dipole cascade model with fixed order matrix elements*, JHEP **05** (2002), 046, [hep-ph/0112284].

[3] F. Krauss, *Matrix elements and parton showers in hadronic interactions*, JHEP **0208** (2002), 015, [hep-ph/0205283].

[4] S. Höche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*, JHEP **05** (2009), 053, [arXiv:0903.1219 [hep-ph]].

[5] K. Hamilton, P. Richardson and J. Tully, *A modified CKKW matrix element merging approach to angular-ordered parton showers*, JHEP **11** (2009), 038, [arXiv:0905.3072 [hep-ph]].

[6] L. Lönnblad and S. Prestel, *Matching Tree-Level Matrix Elements with Interleaved Showers*, JHEP **03** (2012), 019, [arXiv:1109.4829 [hep-ph]].

[7] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, JHEP **06** (2002), 029, [hep-ph/0204244].

[8] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **11** (2004), 040, [hep-ph/0409146].

[9] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, JHEP **11** (2007), 070, [arXiv:0709.2092 [hep-ph]].

[10] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *Automating the POWHEG method in SHERPA*, JHEP **04** (2011), 024, [arXiv:1008.5399 [hep-ph]].

[11] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *A critical appraisal of NLO+PS matching methods*, JHEP **09** (2012), 049, [arXiv:1111.1220 [hep-ph]].

[12] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert and J. Winter, *Event generation with SHERPA 1.1*, JHEP **02** (2009), 007, [arXiv:0811.4622 [hep-ph]].

[13] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *NLO matrix elements and truncated showers*, JHEP **08** (2011), 123, [arXiv:1009.1127 [hep-ph]].

[14] S.~Höche, F.~Krauss, M.~Schönherr and F.~Siegert, *QCD matrix elements + parton showers: The NLO case*, arXiv:1207.5030 [hep-ph].

[15] T.~Gehrmann, S.~Höche, F.~Krauss, M.~Schönherr and F.~Siegert, *NLO QCD matrix elements + parton showers in $e^+e^- \to$hadrons*, arXiv:1207.5031 [hep-ph].

[16] G. Aad et al., ATLAS Collaboration collaboration, *Study of jets produced in association with a W boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, Phys.Rev. **D85** (2012), 092002, [arXiv:1201.1276 [hep-ex]].

[17] G. Aad et al., ATLAS Collaboration collaboration, *Measurement of multi-jet cross sections in proton-proton collisions at a 7 TeV center-of-mass energy*, Eur.Phys.J. **C71** (2011), 1763, [arXiv:1107.2092 [hep-ex]].

[18] S. Chatrchyan et al., CMS Collaboration collaboration, *Measurement of the Ratio of the 3-jet to 2-jet Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV*, Phys.Lett. **B702** (2011), 336–354, [arXiv:1106.0647 [hep-ex]].

[19] S.~Höche, F.~Krauss, M.~Schönherr and F.~Siegert, *W+n-jet predictions with MC@NLO in Sherpa*, arXiv:1201.5882 [hep-ph].

[20] S.~Höche and M.~Schönherr, *Uncertainties in NLO + parton shower matched simulations of inclusive jet and dijet production*, arXiv:1208.2815 [hep-ph].