PROCEEDINGS OF SCIENCE

Multi-jet production in association with an electroweak vector boson

Andreas Papaefstathiou[*†]
Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands.
Nikhef, Theory Group, Science Park 105, 1098 XG, Amsterdam, The Netherlands
E-mail: apapaefs@cern.ch

I will be discussing the production of a single Z or W boson in association with jets at the Large Hadron Collider. I will be presenting results obtained by matching next-to-leading order QCD predictions with the `Herwig 7` and `Pythia 8` parton showers, and by merging all of the underlying matrix elements with up to two light partons at the Born level. These will be compared to several experimental measurements by the ATLAS and CMS collaborations.

XXV International Workshop on Deep-Inelastic Scattering and Related Subjects
3-7 April 2017
University of Birmingham, UK

[*]Speaker.
[†]Work done in collaboration with Rikkert Frederix, Stefano Frixione, Stefan Prestel and Paolo Torrielli.

PoS(DIS2017)175

1. Introduction

1.1 Motivation

The consistent merging of matched multi-jet next-to-leading order (NLO) calculations and the parton shower (PS) constitutes for many processes the state-of-the-art Monte Carlo simulation. It allows for the simultaneous description of several jet observables at NLO or LO both in the hard and soft regions, achieving the "best of both worlds" from fixed-order calculations and parton showers.

1.2 Merging and matching

Several methods have been developed for matching a NLO calculation to the PS. Well-known examples of these are the MC@NLO method [1], the POWHEG method [2], and more recently, the KrKNLO method [3]. Here I will be focussing on the MC@NLO method, which removes the double-counting between the fixed-order calculation and the PS by subtracting explicitly the PS contributions in the NLO. To extend the validity of these methods, one wishes to consistently merge multiple matched calculations together. This extends the scope of matched results to many, well-separated jets.

Several approaches exist, developed over the past decade. These include the MiNLO approach [4], MEPS@NLO within the `Sherpa` Monte Carlo [5, 6], UNLOPS in `Pythia 8` [7], a similar method within the `Herwig 7` framework [8, 9] and a method developed originally by Frederix and Frixione [10, 11] and implemented in the `MadGraph5_aMC@NLO` framework [12, 13]. I will be focussing on the latter method in this talk, abbreviated as 'FxFx' henceforth.

1.3 The FxFx approach

The FxFx method is described in detail in [11]. Here we present the basic elements in a nutshell. The method proceeds as follows:

- MC@NLO samples are constructed for various multiplicities.
- Hard emissions at matrix-element level are suppressed by means of a function.
- The matrix elements are also multiplied by appropriate Sudakov factors.
- The events are showered via `Pythia` or `Herwig`, with appropriate vetoing applied according to distances between hard partons and those resulting after the parton shower.

1.4 Some technical aspects

Here I discuss in brief a couple of technical aspects related to the results presented here. A single Les Houches accord file with 'FxFx' events is generated using `MG5_aMC@NLO`: this contains *all* multiplicities, without the need of separate files. The event file also contains multiple weights for each event. These events are then fed into `Herwig 7` or `Pythia 8`, where the showering and the vetoing are performed, as well as the full Monte Carlo event generation effects such as hadronization, multiple-parton interactions and so on. Finally, the results I will be discussing were constructed using the Rivet [14] analysis framework.

2. Results

2.1 V+jets

The processes involving the production of vector bosons (Z or W) in association with jets constitute important backgrounds to various processes of interest, such as Higgs boson production, top quark production, and models of new physics. They are also interesting in their own right, providing samples with high statistics at experiments, while being theoretically simple, allowing us to investigate regions affected both by Monte Carlo and fixed-order calculations. The results I will be presenting here concern the validation of the 'FxFx' NLO-merging formalism through these processes.

2.2 Miscellaneous details

The V+jets results that follow have been generated with 0, 1 or 2 additional jets. For the showering, hadronization and other effects, `Herwig++ 2.7.1` and `Pythia 8.210` were used, with the parton density set "NNPDF 2.3 NLO". I should emphasize here that the pre-existing Monte Carlo tunes in both event generators were not made for this set, and additionally, the value of the strong coupling constant at the Z pole was set to be the same as in the tunes themselves. Additionally, all the results I will be showing here are straight out of the Monte Carlos, with no rescalings applied. The plots that will be shown contain ATLAS or CMS data points, which in the main panel are compared against the 'FxFx' calculation, that will be show in a green band, which includes the envelope of hard process scale variation, PDF set variation and merging scale variation. For purposes of illustration, the red lines correspond to the "inclusive" MC@NLO matched results. The middle inset presents the same curves normalized to data. The bottom inset shows the envelope of variations for each of the three chosen merging scales: $15, 25, 45$ GeV.

2.3 ATLAS Z+jets at 7 TeV

This ATLAS analysis of [15] studies jet, Z boson, and inclusive properties in Z+jets events and is based on an integrated luminosity of 4.6 fb^{-1} collected at an energy of 7 TeV, using both e^+e and $\mu^+\mu^-$ pairs. The analysis was constructed with $R = 0.4$ anti-kT jets, $p_T(j) > 30$ GeV and $|y(j)| < 4.4$. Further cuts include $p_T(\ell) \geq 20$ GeV, $66 \leq M(\ell^+\ell^-) \leq 116$ GeV, $\Delta R(j\ell) \geq 0.5$, $\Delta R(\ell^+\ell^-) \geq 0.2$, $|\eta(\mu)| \leq 2.4$, $|\eta(e)| \leq 1.37$ and $1.52 \leq |\eta(e)| \leq 2.47$. The transverse momentum (p_T) of the first jet and of the third jet are shown in Fig. 1 and of the fourth jet on the left panel of Fig. 2. The p_T of the first jet is described at NLO, that of the second jet at LO and the fourth jet is generated by the parton shower. It can be seen that there's reasonable agreement between the FxFx predictions and the data, given the uncertainties. The agreement is even good in the case of the fourth jet: this is due to the fact that the other hard jets are well-described already. This provides a reasonable starting point for the parton shower to populate the remaining phase space. The right panel of Fig. 2 shows the exclusive jet multiplicity distribution, demonstrating good agreement up to 7 jets.

2.4 CMS Z+jets at 7 TeV

Next I show results from the CMS study [16] of rapidity distributions in Z+1 jet events at 7 TeV (i.e. exactly one jet), based on an integrated luminosity of 5 fb^{-1}, using both e^-e^+ and

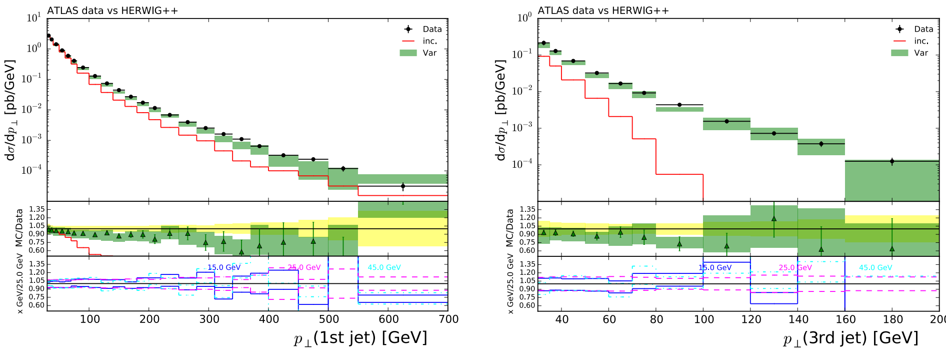

Figure 1: ATLAS results [15] compared to FxFx predictions for the transverse momentum of the first (left) and third jet (right) in Z+jets events.

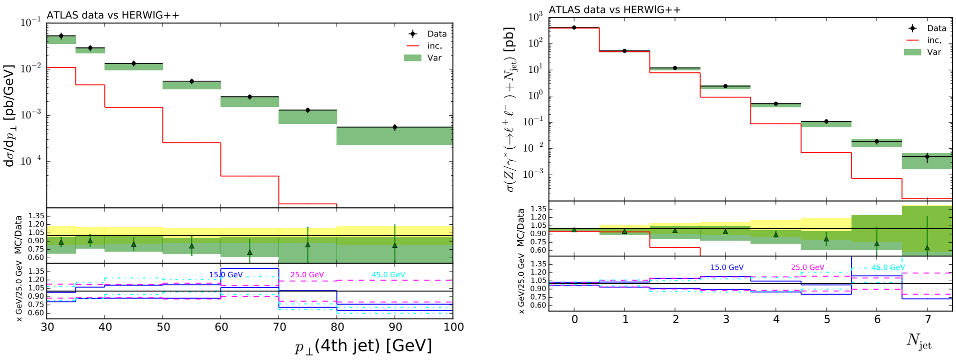

Figure 2: ATLAS results [15] compared to FxFx predictions for the transverse momentum of the fourth jet (left) and the exclusive jet multiplicity distribution (right) in Z+jets events.

$\mu^+\mu^-$ pairs, with $R = 0.5$ anti-kT jets, within $p_T(j) > 30$ GeV and $|\eta(j)| < 2.4$, $p_T(\ell) \geq 20$ GeV, $76 \leq M(\ell^+\ell^-) \leq 106$ GeV, $|\eta(\ell)| \leq 2.1$, $p_T(\ell^+\ell^-) \geq 40$ GeV, $\Delta R(j\ell) \geq 0.5$.

Figure 3 shows the rapidity distance beween the two hardest jets in Z+1 jet events for `Herwig 7` and `Pythia 8`. It is clear that the MC@NLO approach, particularly in the case of `Herwig`, is insufficient to describe this observable.

2.5 CMS, W+jets at 7 TeV

Finally I will show results originating from a 7 TeV CMS analysis [17] of jet, W, inclusive properties, in W+jets events, based on an integrated luminosity of 5 fb^{-1}, using the muon channel, with $R = 0.5$ anti-kT jets, $p_T(j) > 30$ GeV and $|y(j)| < 2.4$, further cuts: $p_T(\mu) > 24$ GeV, $|\eta(\mu)| < 2.1$, $\Delta R(j\mu) \geq 0.5$, $m_T(\mu\nu) > 50$ GeV. Overal the same comments apply for the W+jets data as for the Z+jets data. The FxFx approach improves over the performance of the MC@NLO results, demonstrating the necessity of including higher multiplicities.

3. Conclusions and outlook

I have shown results from samples constructed using the FxFx method in V+jets processes.

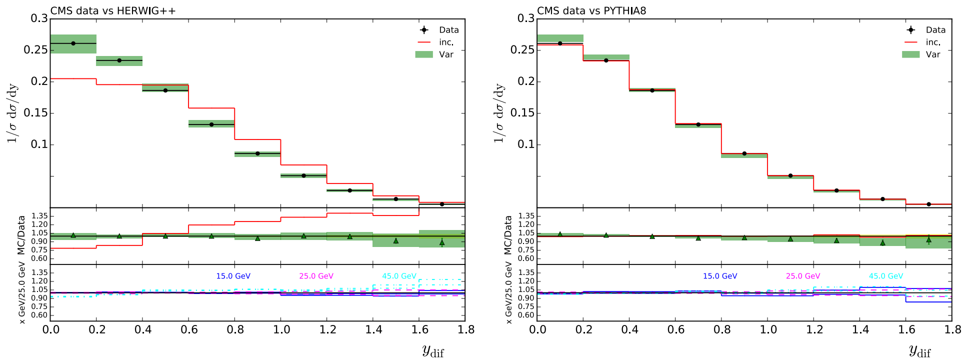

Figure 3: ATLAS results compared to FxFx predictions for the rapidity distance between the two hardest jets in Z+1 jet events for `Herwig 7` (left) and `Pythia 8` (right).

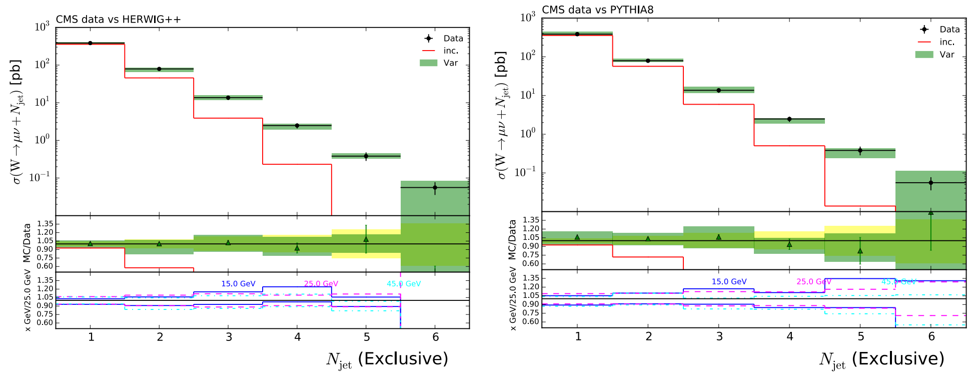

Figure 4: CMS results [16] compared to FxFx predictions for the exclusive jet multiplicity distribution for `Herwig 7` (left) and `Pythia 8` (right) in W+jets events.

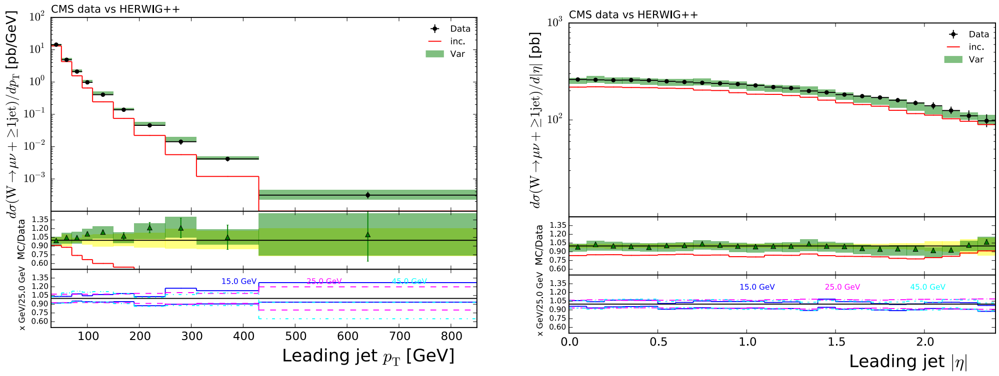

Figure 5: CMS results [16] compared to FxFx predictions for the transverse momentum (left) and pseudo-rapidity (right) of the leading jet in W+jets events.

These were found to describe a wide range of observables very well. The FxFx method has been fully validated using `Herwig 7` and `Pythia 8`, in: Z+jets and W+jets, as well as V+Higgs (see: [18]). Future work involves examining top-anti-top and Higgs boson production in comparison to 13 TeV data.

References

[1] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, *JHEP* **0206** (2002) 029, [hep-ph/0204244].

[2] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **0411** (2004) 040, [hep-ph/0409146].

[3] S. Jadach, W. Placzek, S. Sapeta, A. Siodmok, and M. Skrzypek, *NLO Corrections to Hard Process in Parton Shower MC - KrkNLO Method*, *Acta Phys. Polon.* **B46** (2015), no. 11 2089.

[4] K. Hamilton, P. Nason, and G. Zanderighi, *MINLO: Multi-Scale Improved NLO*, *JHEP* **10** (2012) 155, [arXiv:1206.3572].

[5] T. Gehrmann, S. Hoche, F. Krauss, M. Schonherr, and F. Siegert, *NLO QCD matrix elements + parton showers in e^+e^- —> hadrons*, *JHEP* **01** (2013) 144, [arXiv:1207.5031].

[6] S. Hoeche, F. Krauss, M. Schonherr, and F. Siegert, *QCD matrix elements + parton showers: The NLO case*, *JHEP* **04** (2013) 027, [arXiv:1207.5030].

[7] L. Lonnblad and S. Prestel, *Merging Multi-leg NLO Matrix Elements with Parton Showers*, *JHEP* **03** (2013) 166, [arXiv:1211.7278].

[8] S. Plaetzer, *Controlling inclusive cross sections in parton shower + matrix element merging*, *JHEP* **08** (2013) 114, [arXiv:1211.5467].

[9] J. Bellm et al., *Herwig 7.1 Release Note*, arXiv:1705.0691.

[10] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061, [arXiv:1209.6215].

[11] R. Frederix, S. Frixione, A. Papaefstathiou, S. Prestel, and P. Torrielli, *A study of multi-jet production in association with an electroweak vector boson*, *JHEP* **02** (2016) 131, [arXiv:1511.0084].

[12] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **06** (2011) 128, [arXiv:1106.0522].

[13] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **1407** (2014) 079, [arXiv:1405.0301].

[14] A. Buckley, J. Butterworth, L. Lonnblad, H. Hoeth, J. Monk, et al., *Rivet user manual*, arXiv:1003.0694.

[15] **ATLAS** Collaboration, G. Aad et al., *Measurement of the production cross section of jets in association with a Z boson in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector*, *JHEP* **07** (2013) 032, [arXiv:1304.7098].

[16] **CMS** Collaboration, S. Chatrchyan et al., *Rapidity distributions in exclusive Z + jet and γ + jet events in pp collisions at $\sqrt{s}$ = 7 TeV*, *Phys. Rev.* **D88** (2013), no. 11 112009, [arXiv:1310.3082].

[17] **CMS** Collaboration, V. Khachatryan et al., *Differential cross section measurements for the production of a W boson in association with jets in protonâĂŞproton collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett.* **B741** (2015) 12–37, [arXiv:1406.7533].

[18] **LHC Higgs Cross Section Working Group** Collaboration, D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, arXiv:1610.0792.