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High multiplicity processes with BlackHat and Sherpa

Zvi Bern, Kemal Ozeren
Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095-1547, USA
E-mail: `bern@physics.ucla.edu`, `ozeren@physics.ucla.edu`

Stefan Höche
SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA
E-mail: `lance@slac.stanford.edu`, `shoeche@slac.stanford.edu`

Fernando Febres Cordero
Departamento de Física, Universidad Simón Bolívar, Caracas 1080A, Venezuela
E-mail: `ffebres@usb.ve`

Harald Ita
Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, D-79104 Freiburg, Germany
E-mail: `harald.ita@physik.uni-freiburg.de`

David Kosower, Nicola Adriano Lo Presti
Institut de Physique Théorique, CEA–Saclay, F–91191 Gif-sur-Yvette cedex, France
E-mail: `david.kosower@cea.fr`, `nicola.lo-presti@cea.fr`

Stephanie Bartle, Jeppe R. Andersen, Daniel Maître[*]
Institute for Particle Physics Phenomenology, Department of Physics, University of Durham, DH1 3LE, UK
E-mail: `stephanie.bartle@durham.ac.uk`, `jeppe.andersen@durham.ac.uk`, `daniel.maitre@durham.ac.uk`

In this contribution, we present an intermediate storage format for next-to-leading order (NLO) events and explain the advantages of presenting a NLO calculation in this format. We also present some recent applications, including the calculation of PDF uncertainties and the combination of different multiplicity samples for the prediction of gap fractions in inclusive dijet events.

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[*] Speaker.

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1. Introduction

In recent years much progress has been achieved in the calculation of QCD predictions to next-to-leading order (NLO) accuracy (for a summary, see ref. [1]). Even with these advances, high-multiplicity processes, though now feasible, remain computationally expensive. In this contribution, we report on a method of using specialized event files, which we call *n*-tuple files, to reduce the cost of fixed-order NLO calculations. This is important as more and more techniques such as NLO parton-shower matching and merging use them as an input. For example, the event files described in this contribution have been used within the LoopSim method [2] to merge NLO calculations for Z+1 jet and Z+2 jets [3]. In the next section we describe the *n*-tuple files and a library for their use. In the third section we show some applications of the *n*-tuple files.

2. n-Tuples

Next-to-Leading Order (NLO) calculations are computationally intensive, which means that under normal circumstances computing new observables with new cuts is a tedious task. The most computationally demanding part is the calculation of the matrix elements; other operations such as jet clustering, the evaluation of the parton distribution functions and the calculation of the observables are relatively cheap. We can amortize the cost of the matrix element calculation by storing the matrix elements and the phase-space information along with a few coefficients of the logarithms driving the scale dependence in a file. These files can then be re-read to obtain an analysis with different cuts or observables, or to yield the result one would have obtained with a different PDF or a different choice of renormalization or factorization scale. This is especially useful when computing PDF uncertainties that would otherwise require the same matrix element to be recomputed a large number of times.

The ROOT [4] format has been chosen as a backend to store the matrix elements and associated information. Table 1 details the hadronic center of mass energy and minimum transverse momentum cuts applied on the jets for each processes available in the *n*-tuple format. Details about the calculation for the creation of these files can be found in refs. [5, 6, 7, 8, 9, 10, 11].

NLO event files such as the one we describe here and in ref. [12] have the added advantage of making it easier to communicate challenging NLO computations with the experimental community.

Along with the *n*-tuple files we provide a C++ library for accessing the information they contain. It can either be used out of the box or as a template for a dedicated implementation in a different framework. The library also provides a python interface. Figure 1 shows an example of the usage of the library to read a *n*-tuple file (and in this case display the stored momenta instead of using them to compute an observable or verifying that this particular event passes the analysis cuts.) Figure 2 shows an example of the usage of the library to change the factorization and renormalization scale for a new prediction.

In t next section we present some applications of this method that would have been too prohibitive in CPU time to perform using straightforward repeated evaluation of the matrix elements.

```
import nTupleReader as NR
r=NR.nTupleReader()

r.addFile("sample.root")

while r.nextEntry():
        for i in range(r.getParticleNumber()):
                print "p(%d)=(%f,%f,%f,%f)" % (
                 i,
                 r.getEnergy(i),
                 r.getX(i),
                 r.getY(i),
                 r.getZ(i)
                )
```

Figure 1: Example of the usage of the nTupleReader library. The example uses the python interface of the library.

```
import nTupleReader as NR
r=NR.nTupleReader()
r.addFile("sample.root")

r.setPDF("CT10nlo.LHgrid")
r.setPDFmember(12)

while r.nextEntry():
        # compute new scales
        RenScale = ....
        FacScale = ....
        newWeight=r.computeWeight(FacScale,RenScale)
        # use this weight in the analysis
        ...
```

Figure 2: Example of the usage of change of scales using the nTupleReader library. The example uses the python interface of the library.

Process	energy	pt cut
$W^+(\to e^+\nu_e)+1,2,3,4$ jets	7 TeV	25 GeV
$W^+(\to e^+\nu_e)+1,2,3$ jets	8 TeV	20 GeV
$W^-(\to e^-\bar{\nu}_e)+1,2,3,4$ jets	7 TeV	25 GeV
$W^-(\to e^-\bar{\nu}_e)+1,2,3$ jets	8 TeV	20 GeV
$Z(\to e^+e^-)+1,2$ jets	7 TeV	25 GeV
$Z(\to e^+e^-)+3,4$ jets	7 TeV	20 GeV
$Z(\to e^+e^-)+1,2,3$ jets	8 TeV	20 GeV
n jets $(n=1,2,3,4)$	7 TeV	40 GeV
n jets $(n=1,2,3,4)$	8 TeV	40 GeV

Table 1: Available processes at NLO. The decay of the vector boson into a lepton pair is always included.

3. Applications

3.1 Jet Veto

Understanding the impact of jet vetoes is very important for current Higgs studies. The behavior of observables when a jet veto is applied can be investigated in processes that are under better theoretical control than Higgs production. New calculations or techniques can be checked against data for simpler processes and that knowledge can be used to improve the our understanding of Higgs or BSM measurements. One interesting observable for the investigation of jet veto efficiencies is the gap fraction g, which is defined as the probability of having no jet above a threshold Q_0 between the two tagging jets:

$$g=\frac{\sigma_{Y/pt}(Q_0)}{\sigma_{tot}}$$

where $\sigma_{Y/p_T}(Q_0)$ is the cross section when vetoing jets with both transverse momentum above the threshold Q_0 and rapidity between that of the tagging jets. These can be either the two highest transverse momentum jets (σ_{p_T}) or the most forward/backward ones (σ_Y). σ_{tot} is the total cross section without the jet veto. We use the notation

$$\sigma_{g=n}\ ,\ \sigma_{g\geq n}$$

to denote the cross section with exactly n jets in the gap , or n jets or more in the gap, respectively.

Restricting the precision of the fixed order prediction to NLO, one can give a prediction for the gap fraction in two different ways. First, one could use only one NLO calculation for each of the numerator or denominator:

$$\begin{aligned} g &= \frac{\sigma_{g=0}}{\sigma_{tot}}=1-\frac{\sigma_{g\geq 1}}{\sigma_{tot}} \\ &= 1-\frac{\sigma^{\mathrm{nlo},j\geq 3}_{g\geq 1}}{\sigma^{\mathrm{nlo},j\geq 2}}=1-\frac{\sigma^{\mathrm{nlo},j\geq 3}-\sigma^{\mathrm{nlo},j=3}_{g=0}-\sigma^{\mathrm{lo},j=4}_{g=0}}{\sigma^{\mathrm{nlo},j\geq 2}}\ . \end{aligned} \tag{3.1}$$

Alternatively one can try to use more NLO calculations

$$g=\frac{\sigma_{g=0}}{\sigma_{tot}}=\frac{\sigma^{\mathrm{nlo},j=2}_{g=0}+\sigma^{\mathrm{nlo},j=3}_{g=0}+\sigma^{\mathrm{nlo},j\geq 4}_{g=0}}{\sigma^{\mathrm{nlo},j=2}+\sigma^{\mathrm{nlo},j=3}+\sigma^{\mathrm{nlo},j\geq 4}}\ . \tag{3.2}$$

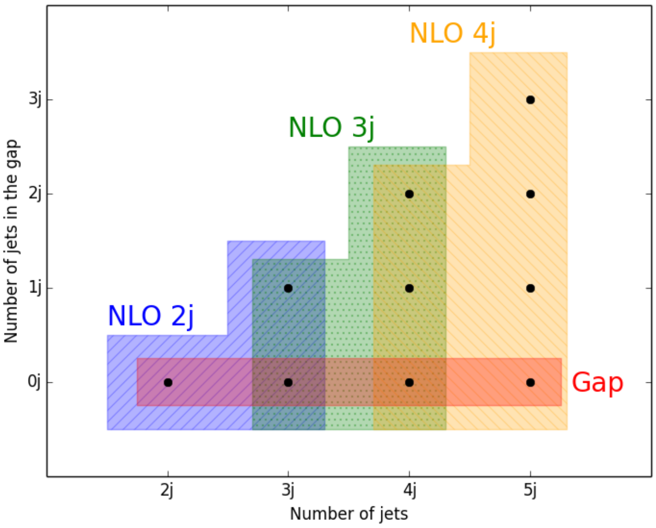

Figure 3: Each dot represent a possible contribution.

The two formulae are formally of the same order. Figure 3 illustrates the different contributions in the plane spanned by the number of jets and the number of jets in the gap. Each term in the formulae above can be identified in this plane.

The left pane of figure 4 shows the gap fraction as a function of the rapidity separation of the tagging jets. The different sets of curves correspond to different bins in the average transverse momentum of the two tagging jets $\bar{p}_T$. Each set of curves is offset with respect to the lower $\bar{p}_T$ set by 0.5. The bins are

$$\begin{aligned} 240\,\mathrm{GeV} < \ &\bar{p}_T < 270\,\mathrm{GeV} \\ 210\,\mathrm{GeV} < \ &\bar{p}_T < 240\,\mathrm{GeV} \\ 180\,\mathrm{GeV} < \ &\bar{p}_T < 210\,\mathrm{GeV} \\ 150\,\mathrm{GeV} < \ &\bar{p}_T < 180\,\mathrm{GeV} \\ 120\,\mathrm{GeV} < \ &\bar{p}_T < 150\,\mathrm{GeV} \\ 90\,\mathrm{GeV} < \ &\bar{p}_T < 120\,\mathrm{GeV} \\ 70\,\mathrm{GeV} < \ &\bar{p}_T < 90\,\mathrm{GeV} \end{aligned} \tag{3.3}$$

The data points are from the ATLAS measurement [13]. We provide theoretical predictions obtained using HEJ [14, 15, 16] and NLO predictions obtained by BlackHat+Sherpa [17, 11, 18, 19, 20, 21].

The right pane of figure 4 shows the ratio to the data for each $\bar{p}_T$ bin. The green band represents the HEJ prediction while the blue and red curves correspond to the NLO predictions of formulae (3.1) and (3.2), respectively. The bands represent only the statistical Monte Carlo integration errors.

3.2 PDF uncertainties

PDF uncertainties are usually computationally intensive, as the same calculation has to be

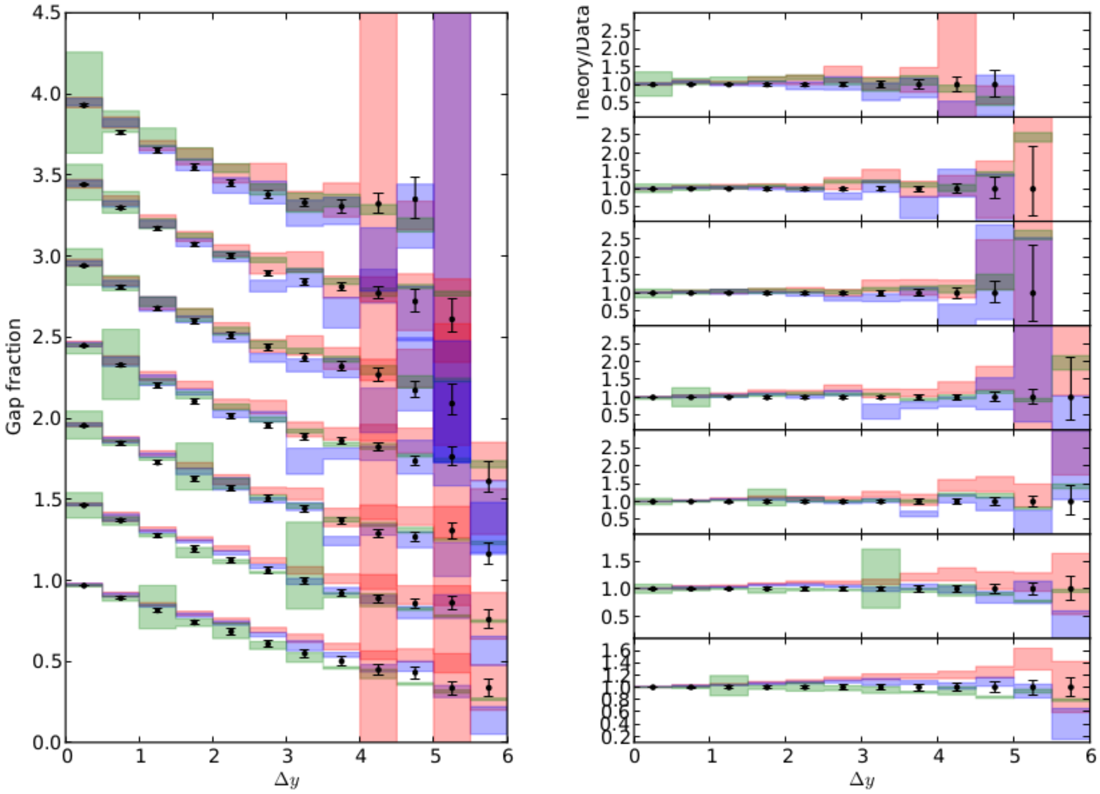

Figure 4: Gap fraction as a function of Δy for various slices of $\bar{p}_T$. The jets defining $\bar{p}_T$ and Δy are the two jets with the largest p_T.

preformed with a large number of slightly different PDF fits. Using n-tuple files the expensive part of the calculation need be performed only once (and in this case it had been done previously, so we get the results at almost no computational cost). Figure 5 shows the ratio of the first jet transverse momentum in W^-+4 jets and W^++ 4 jets. This ratio is evaluated for different PDFs and the associated uncertainties are shown in the lower pane. We have used the NNPDF21 [22], MSTW2008 [23], CT10 [24] and ABM11 [25] PDF sets. The bands for NNPDF provides the 1-σ error bands, for MSTW2008 we used the 68% confidence level uncertainty estimate, for CT10 the bands represent the 90% confidence level uncertainty estimate. The errors provided with the ABM set represent a 1-σ deviation from the best fit. Figure 6 shows the rapidity of the second jet in events with a Z boson and 4 jets.

4. Conclusions

In this contribution we have described a format for NLO events and shown some applications.

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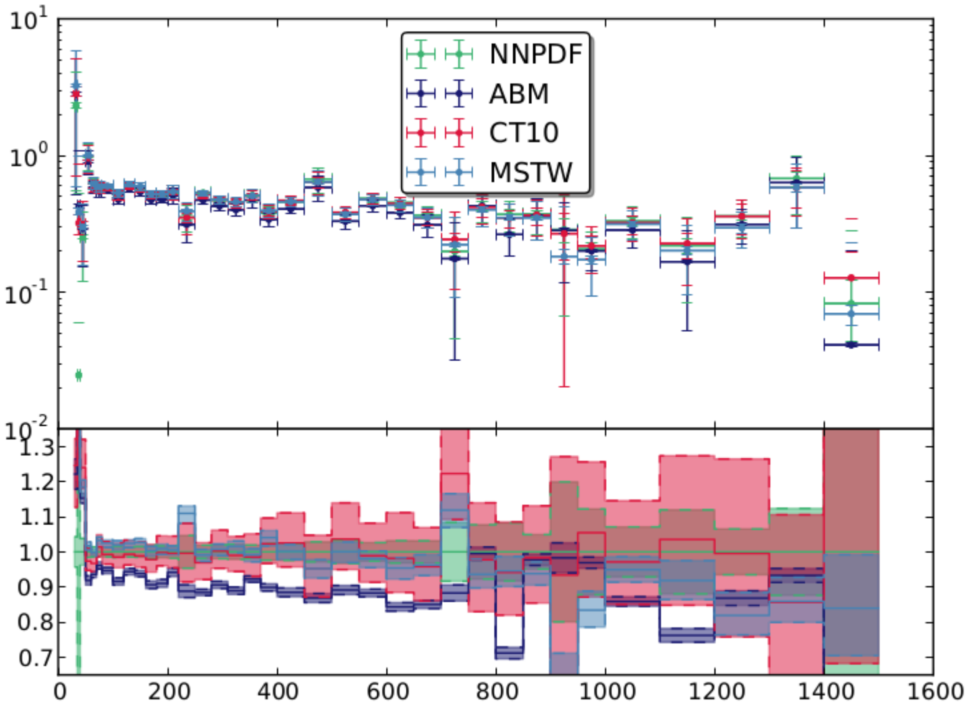

Figure 5: W^-+4 jets to W^+ + 4 jets ratio for the first jet transverse momentum for different PDF sets. The lower pane shows the ratio to the NNPDF prediction. The different color bands display the uncertainties.

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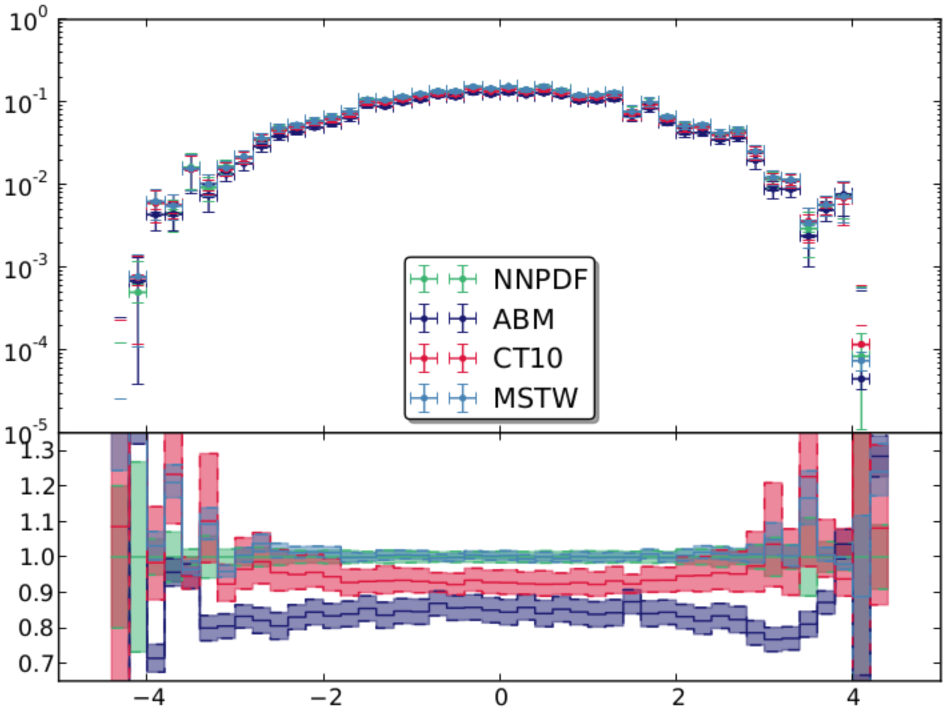

Figure 6: Second jet rapidity in Z+4 jets events.

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