The High Energy Jets Framework

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High Energy Jets provides an all-order description of wide-angle QCD emissions, resumming the leading-logarithmic contributions in the high-energy limit. In this contribution, we briefly summarise the approach and its implementation in a flexible Monte Carlo event generator. We discuss comparisons between HEJ and recent LHC data and then go on to probe the similarities and differences in the results obtained from High Energy Jets and other theoretical frameworks in inclusive dijet and W+dijet production.

1 Introduction to High Energy Jets (HEJ)

Accurate theoretical descriptions of multi-jet production are of key importance to physics at the Large Hadron Collider. This is our first opportunity to test our theoretical understanding of QCD at these high energies, and this will be key to reaching the full potential of the LHC physics programme. For example, the results of comprehensive analyses of multi-jet radiation with current data will be used when applying a jet veto to the production of a Higgs boson in association with jets.

It has already been seen in the 7 TeV LHC data that the ratio between inclusive $(n+1)$-jet rates and inclusive n-jet rates can be large. While this is true for the ratios of the cross sections, the effect is particularly large in certain key regions of phase space including high momentum regions (see e.g. high H_T in [1]) or events where there is a large rapidity separation between jets (see e.g. [2]).

Motivated by the large impact of higher order corrections, the High Energy Jets (HEJ) framework [3, 4, 5] provides an all-order resummation of the dominant (leading-log) contributions to wide-angle, hard QCD radiation in the High Energy limit. In this limit, scattering amplitudes factorise into rapidity-ordered pieces. This structure allows an extremely efficient description of many-particle hard-scattering matrix elements. This forms the basis of the HEJ description which has been developed for the production of jets, and also W, Z and Higgs boson production in association with jets. The High Energy limit can be stated as

$$s_{ij} \to \infty \ \forall \ \{i,j\}, \quad |p_{\perp,i}| \text{ fixed}, \tag{1}$$

where i, j label outgoing quarks and gluons. In practice this corresponds to wide-angle QCD emissions and may be stated equivalently in terms of pairwise rapidity differences becoming large while transverse momenta components remain finite. This is in contrast to the soft and collinear emissions which are included in a parton shower resummation. A complete jet description can be achieved by consistently merging the two approaches [6].

The derivation of the building blocks of the HEJ framework has been described in detail in [3, 4]. The implementation of these for multi-jet production in a fully flexible event generator is described further in [5], and the generator itself is publicly available at `www.cern.ch/hej`.

Predictions from HEJ have been used in analyses by ATLAS [2] and by CMS [7, 8]. The ATLAS study was a study of jet radiation with a jet veto across a wide range of transverse momenta and rapidities. HEJ gave a consistently good description of data throughout. Discrepancies were only seen in cases where cuts had induced a large hierarchy of transverse momentum scales, as this evolution is not systematically included in the parton-level predictions. In the central-forward CMS study [7] which separated the jets in rapidity, HEJ again gave a good description of data where more traditional approaches performed less well. In a subsequent jet study [8], the HEJ predictions showed slight deviation from data at large rapidity differences; work is ongoing to evaluate the uncertainties in this case.

Overall, HEJ has given an excellent description of early data, and in some cases has outperformed other more standard approaches. This underlines the importance of the higher order contributions included in HEJ. In the rest of this contribution, we probe to what extent data could probe the differences between the HEJ approach and that of other theoretical frameworks which are built upon fixed-order matrix elements.

2 Comparisons Between Theoretical Approaches

We begin by comparing HEJ and POWHEG [9, 10] predictions for dijet production. The HEJ framework is an all-order resummation of wide-angle QCD radiation which includes, for events which result in four or fewer jets, matching to leading-order matrix elements. In contrast, the POWHEG description of multi-jet production begins with a next-to-leading order (NLO) matrix element, which is then supplemented with a resummation from a parton shower. It is surprising, then, that the predictions from the two approaches have been seen to be very similar (see [2]). The extent to which these descriptions can be distinguished was studied recently in [11].

In order to implement cuts which do not induce a large hierarchy in transverse momentum between the jets, a minimal set is used:

$$p_{\perp,j} > 35 \text{ GeV}, \quad p_{\perp,j_1} > 45 \text{ GeV}, \quad |y_j| < 4.7. \qquad (2)$$

The additional cut on the hardest jet is in order to allow a meaningful comparison with the pure NLO calculation. Neither the POWHEG or HEJ descriptions suffer from an instability in the presence of symmetric cuts.

The left plot in figure 1 shows the predictions for the average number of jets as a function of the rapidity difference between the most forward and most backward jet in each event, Δy_{fb}. The bands around the HEJ and NLO predictions indicate the result of varying the renormalisation and factorisation scales by a factor of two in each direction. The vertical lines indicate statistical uncertainty. In this plot, all the predictions show an increase in the average number of jets with Δy_{fb}, with the largest increase being seen in the HEJ prediction, as expected. The lowest prediction comes from the pure NLO calculation, followed by the POWHEG first emission, then the full POWHEG+PYTHIA shower, which increases to a value around 2.6 for $\Delta y_{fb} = 7$.

The same variable is shown in the right plot in figure 1, but now as a function of H_T. It is immediately clear from the different behaviour that a different region of phase space is now being probed. As H_T increases, the largest prediction now comes from the POWHEG+PYTHIA

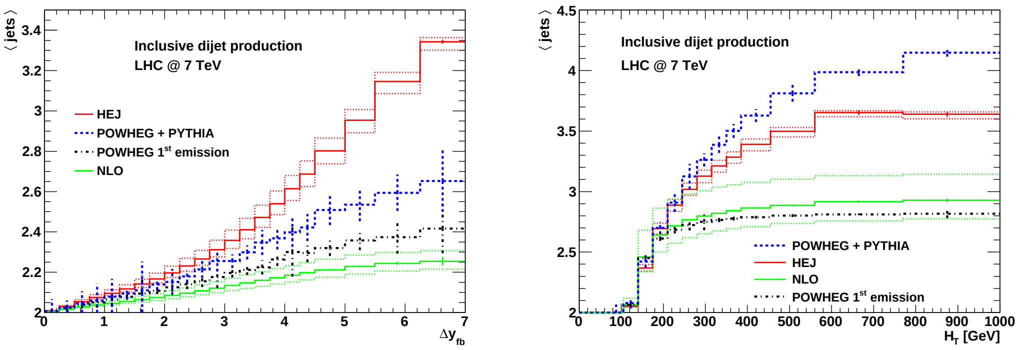

Figure 1: The average number of jets as a function of (left) the difference in rapidity between most forward and most backward jet, and (right) as a function of H_T. Plots taken from [11].

prediction which peaks above an *average* value of 4 jets per event, which is remarkably high for an inclusive dijet sample. The HEJ prediction levels off a little below this around 3.6. The NLO and POWHEG 1st emission predictions are restricted to lie below 3, and both reach values close to that.

The differences in the predictions here appear to be significant enough that one could hope to distinguish between the approaches with LHC data. Other variables were also studied in [11], which showed smaller differences. For example, when a measure of the azimuthal decorrelation of the jets (which results from hard radiation) is studied as a function of Δy_{fb}, the predictions from HEJ and POWHEG+PYTHIA are extremely similar until values of $\Delta y_{fb} > 6$.

A related study has been performed in the context of W boson production in association with jets in [12]. Here, predictions from four theoretical approaches were compared: NLO and a merged NLO sample both from BlackHat [13, 14, 15], a merged matrix-element plus parton shower sample from Sherpa [16, 17, 18] and HEJ [19]. Figure 2 shows the predictions for the average number of jets now for this process. In the left plot, it can again be clearly seen that the predictions all rise with Δy_{fb}. In this case, there is a high level of agreement between the predictions until large values of Δy, with only the pure NLO prediction lying slightly below.

In the right-hand plot of figure 2, the average number of jets for W+jets is shown as a function now of H_T. Here, the SHERPA and Exclusive NLO sums predictions give the highest value for large H_T, peaking around a value of 4. The HEJ prediction here is lower, and closer to the pure NLO result around 3. It should be possible to distinguish between these with data.

3 Summary

The High Energy Jets framework provides an alternative method to describing multi-jet production, which is based on an all-order resummation of hard, wide-angle QCD radiation. It has already been seen to give a good description of early LHC data. Analyses which may be able to distinguish between different theoretical descriptions in jets and W+jets have been discussed. For example, the average number of jets as a function of H_T shows large differences between different theoretical approaches for both processes.

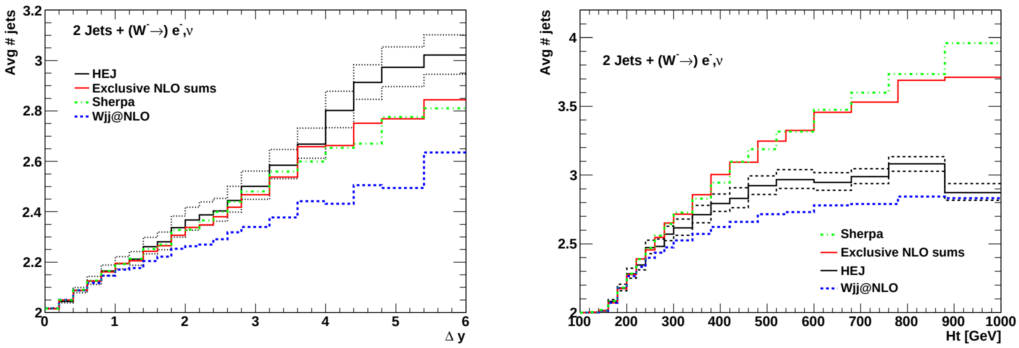

Figure 2: A comparison of the predictions for the average number of jets in an inclusive W+dijet sample from different theoretical descriptions as a function of (left) the difference in rapidity between most forward and most backward jet, and (right) as a function of H_T. Plots taken from [12].

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