Energy flow observables in hadronic collisions

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2012-03/52

We present recent QCD calculations of energy flow distributions associated with the production of jets at wide rapidity separations in high-energy hadron collisions, and discuss the role of these observables to analyze contributions from parton showering and from multiple parton collisions.

Jet rates and event shape variables have long been used [1] to characterize QCD final states from hard scatter events at high-energy colliders and to describe the event's energy flow. Jet shape variables describing the jet's internal structure and the energy flow within a jet have also been studied, and are being proposed [2] as diagnostic tools at the LHC in searches for potential new physics signals from highly boosted massive states. In the last year first LHC measurements of event shapes [3] and jet shapes [4] have been performed.

In all these cases, the interpretation of results depends on a good understanding of the overall structure of the final states. This in turn implies controlling effects due to strong interaction dynamics in the initial state. Thus for instance jet shape observables such as [5, 6] that are sensitive to the jet's substructure are also sensitive to soft physics effects, including the underlying event, pile-up, and multiple parton interactions [7, 8]. Hadronic event shapes measured at the LHC [3] suggest that parton showering effects dominate contributions of hard matrix elements evaluated at high multiplicity.

In this article we focus on parton showering and multi-parton interactions (for recent discussions reviewing these topics, see respectively [9] and [10, 11]), and we discuss energy flow observables [12] which become measurable, essentially for the first time, at the LHC, and may be used for studies of showering and of multiple collisions. The main focus is on the region of high rapidities, where production of final states with sizeable momentum transfers presents new features at the LHC compared to previous collider experiments [7]. Thus we consider final states associated with the production of two jets widely separated in rapidity [13, 14]. To be specific, we consider correlations of a forward and a central jet (Fig. 1), and investigate the associated transverse energy flow as a function of pseudorapidity and azimuthal angle in the transverse plane [12].

The region of high rapidities is critical. While first measurements of forward jet spectra at the LHC [15] are roughly in agreement with predictions from different Monte Carlo simulations, detailed aspects of production rates and correlations [15, 16] are not well understood yet. From the underlying event standpoint [17, 18], energy flow measurements [19] in minimum bias and dijet events emphasize the difficulty [20] in achieving a unified underlying event description from central to forward rapidities based on Pythia [21] Monte Carlo tuning.

Ref. [12] considers production of central and forward jets (taking e.g. central and forward

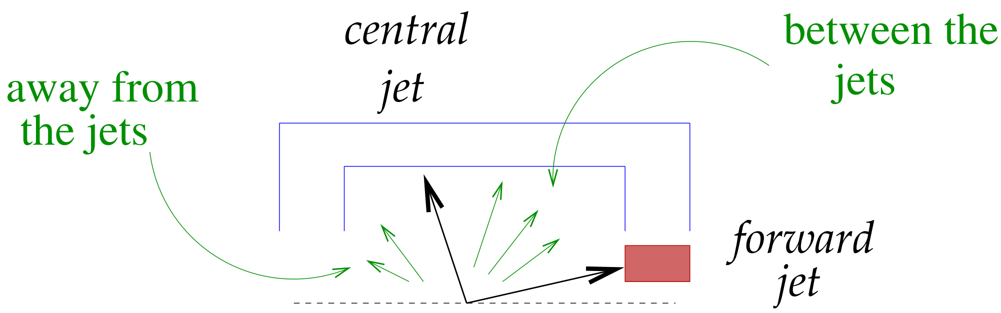

Figure 1: *Production of forward and central jets: energy flow in the inter-jet and outside regions.*

jet pseudorapidities in the range $1 < \eta_c < 2, \ \ -5 < \eta_f < -4$), and the transverse energy flow

$$\frac{dE_\perp}{d\eta} = \frac{1}{\sigma} \int dq_\perp \ q_\perp \ \frac{d\sigma}{dq_\perp \ d\eta} \ \ .$$

While the measurements [19] are designed to investigate properties of the soft underlying event, this energy flow observable is sensitive to harder color radiation. Also, it enables one to access more details on the structure of the final states associated with the jet production processes observed in [15, 16]. The transverse factor $q_\perp$ in the above energy flow distribution enhances matrix element corrections due to extra hard-parton emission at short distances, and gives contributions which break the transverse momentum ordering approximation in the long-distance evolution of the parton showers. Ref. [12] computes these effects in the high-energy factorization framework [14, 22].

The transverse energy flow, obtained by summing the energies over all particles in the final states, is naturally also sensitive to soft particles being produced into the final states. In order to study hard radiation one may rather consider the associated charged particle p_T spectra. However, at the LHC it is possible to control the infrared sensitivity of the energy flow by looking at an alternative observable, defined in a different manner [12] as follows. One may first cluster particles into jets by means of a jet algorithm, and then construct the associated energy flow from jets with transverse energy above a given lower bound q_0. Infrared safety is ensured by running a jet algorithm, as opposed to applying the bound on the energy flow integral. The question is which value of q_0 is phenomenologically meaningful. At the LHC the transverse energy per unit rapidity is large enough across a wide rapidity range that a mini-jet type of bound $q_0 \approx 5$ GeV should be feasible. This is to be contrasted with previous collider experiments, where one either did not have the detector capabilities to go very forward in rapidity (as at the Tevatron) or did not have enough transverse energy per unit rapidity (as at HERA, about $1 \div 2$ GeV per unit rapidity). Calorimetric measurements of this mini-jet energy flow at the LHC will be interesting.

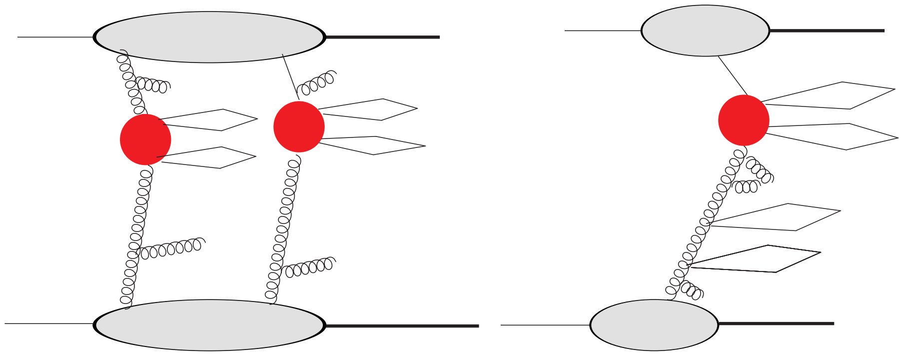

Figure 2: *Multi-jet production by (left) multiple parton collisions; (right) single parton collision.*

Multiple parton collisions (Fig. 2) form one of the major motivations for such energy flow studies. Multiple collisions become increasingly important with energy as parton densities grow [23], contributing primarily to highly differential cross sections sensitive to the detailed distribution of the states produced by parton evolution. Their role at the LHC is being studied very actively both by experiment [8, 18, 20] and theory [8, 10, 11, 24]. Since multi-parton interactions depend on the growth of parton densities and probe the detailed final-state structure, their treatment should be affected by corrections to parton shower evolution. Collinear ordering is known to give an effective picture of parton evolution for inclusive observables; however, it is not expected to represent the detailed final states reliably when longitudinal momentum fractions x become small and parton densities increase. So, in particular, noncollinear high-energy corrections to QCD showers could affect the analysis of multiple interactions significantly [7, 25]. The energy flow in forward-central jet production may provide a first step to analyze this issue.

Figs. 3 and 4 report results for the energy flow [12] from three Monte Carlo event generators: the $k_\perp$-shower Cascade generator [26], to evaluate contributions of high-energy logarithmic corrections; the NLO matched Powheg generator [27], to evaluate the effects of NLO corrections to matrix elements; Pythia Monte Carlo [21], used in two different modes: with the LHC tune Z1 [28] (Pythia-mpi) to evaluate contributions of multi-parton interactions, and without any multi-parton interactions (Pythia-nompi).

Fig. 3 shows the pseudorapidity dependence of the transverse energy flow in the region between the central and forward jets. The particle energy flow plot on the left in Fig. 3 shows the jet profile picture, and indicates enhancements of the energy flow in the inter-jet region with respect to the Pythia-nompi result from higher order emissions in Cascade and from multiple parton collisions in Pythia-mpi. On the other hand, there is little effect from the next-to-leading hard correction in Powheg with respect to Pythia-nompi. The energy flow is dominated by multiple-radiation, parton-shower effects. The mini-jet energy flow plot on the right in Fig. 3 indicates similar effects, with reduced sensitivity to infrared radiation. As the mini-jet flow definition suppresses the contribution of soft radiation, the Cascade and Pythia-mpi results become more similar in the inter-jet region. Distinctive effects are also found in [12] by computations in the region away from the jets.

Fig. 4 illustrates the azimuthal dependence of the mini-jet transverse energy flow. Here $\Delta\phi$ is measured with respect to the central jet. The $\Delta\phi$ distribution is shown for three different

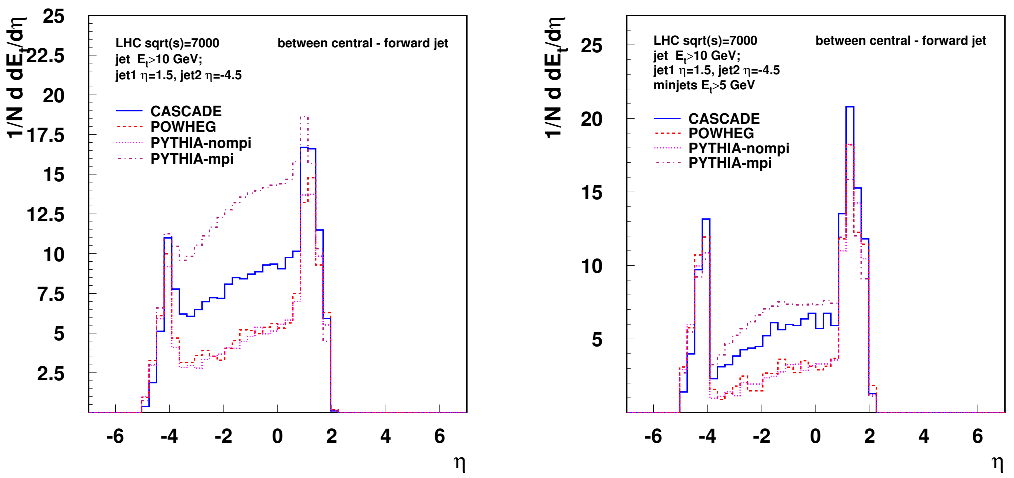

Figure 3: *Transverse energy flow [12] in the inter-jet region: (left) particle flow; (right) mini-jet flow.*

rapidity ranges, corresponding to the central-jet, forward-jet, and intermediate rapidities. As we go toward forward rapidity, the CASCADE and PYTHIA-mpi calculations give a more pronounced flattening of the $\Delta\phi$ distribution compared to POWHEG and PYTHIA-nompi, corresponding to increased decorrelation between the jets.

The above numerical results indicate that quite distinctive behaviors should be expected from measurements of particle and mini-jet energy flows associated with production of forward and central jets. They will tell us about several soft-physics effects, from the structure of underlying events to multiple parton collisions to QCD showering, which are relevant to a range of subjects in LHC physics: from studies of color flow in the QCD tuning of Monte Carlo event generators to searches for new physics signals based on the structure of jets. One feature emerging already from the above studies is that gluon emission over large rapidity intervals gives sizeable contribution to the inter-jet energy flow. As a result, the rates for multi-parton interactions may be influenced significantly by non-collinear corrections to single-chain showering. From the theory viewpoint, it underlines the relevance of approaches which aim at a more accurate and complete description of initial state dynamics by generalizing the notion of parton distributions, both for quark-dominated [29] and gluon-dominated [30] processes.

Acknowledgments. I thank the convenors for the invitation to a very nice workshop. The results in this article have been obtained in collaboration with M. Deak, H. Jung and K. Kutak.

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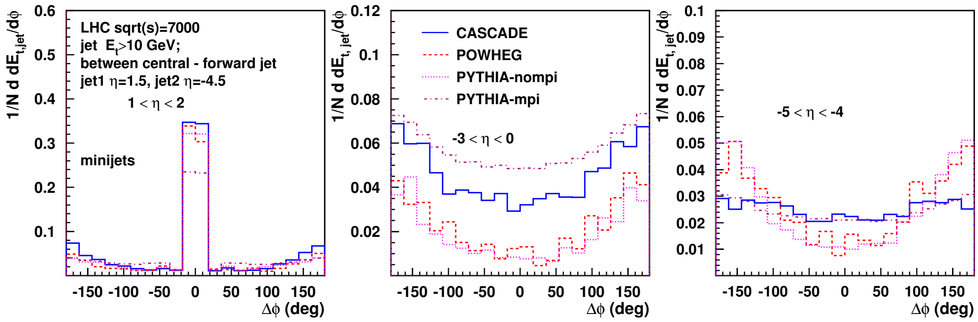

Figure 4: *Azimuthal dependence of the mini-jet energy flow [12] for different rapidity ranges: (left) central-jet; (middle) intermediate; (right) forward-jet.*

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