Transverse Energy Flow with Forward and Central Jets at the LHC

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At the LHC, using forward + central detectors, it becomes possible for the first time to carry out measurements of the transverse energy flow due to “minijets” accompanying production of two jets separated by a large rapidity interval. We discuss parton-shower calculations of energy flow observables in a high-energy factorized Monte Carlo framework, and comment on the role of these observables to study high parton multiplicity effects.

The production of final states created with high momentum transfers and boosted to forward rapidities is a new feature of the Large Hadron Collider compared to previous collider experiments, subject of intense experimental and theoretical activity\textsuperscript{[1,2,3]}. Forward high-$p_{\perp}$ production enters the LHC physics program in both new particle discovery processes (e.g., jet studies in decays of boosted massive states\textsuperscript{[2]}) and new aspects of standard model physics (e.g., QCD at small $x$ and its interplay with cosmic ray physics\textsuperscript{[3]}).

Investigating such final states poses new challenges to both experiment and theory. On one hand, measurements of jet observables in the forward region call for new experimental tools and analysis techniques\textsuperscript{[1,4,5,6,7,8,9,10,11,12,13]}. On the other hand, the evaluation of QCD theoretical predictions is made complex by the forward kinematics forcing high-$p_{\perp}$ production into a region characterized by multiple hard scales, possibly widely disparate from each other. This raises the issue of whether potentially large corrections arise beyond finite-order perturbation theory which call for perturbative QCD resummations\textsuperscript{[6,7,8,9]} and/or contributions beyond single parton interaction\textsuperscript{[10,11,12,13]}. It is thus relevant to ask to what extent current Monte Carlo generators can provide realistic event simulations of forward particle production, and how LHC experimental measurements can help improve our understanding of QCD effects in the forward region.

To this end, Refs.\textsuperscript{[8,9,14]} have proposed measuring correlations of a forward and a central jet and performed a numerical analysis of the effects of noncollinear, high-energy corrections to initial-state QCD showers. First experimental studies have since appeared in preliminary form in\textsuperscript{[15]}. Ref.\textsuperscript{[16]} has further pointed out that the capabilities of forward + central detectors at the LHC allow one to perform detailed investigations of the event structure by measuring the associated transverse energy flow as a function of rapidity, both in the interjet region and in the region away from the trigger jets. Such energy flow measurements have not been made before at hadron-hadron colliders. Measurements of this kind were made in lepton-proton collisions at HERA, where one had roughly an average transverse energy flow of 2 GeV per unit rapidity\textsuperscript{[17]}. This increases by a factor of five at the LHC to about 10 GeV or more per unit rapidity out to forward rapidity, as a result of the large phase space opening up for high-$p_{\perp}$ production. Then it becomes possible to carry out measurements of the flow resulting from “mini-jets” with transverse energy above a few GeV, thus suppressing the sensitivity of the observable to soft particle production. Ref.\textsuperscript{[16]} suggests this minijet energy flow as a way to investigate the detailed structure of events with forward and central jets.

These measurements could be viewed as complementary to measurements performed by the CMS Collaboration\textsuperscript{[15]} on the energy flow in the forward direction in minimum bias events and in events containing a central dijet system. The studies\textsuperscript{[18]} are designed to investigate properties of the soft underlying event; in particular, they illustrate that the energy flow observed in the

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forward region is not well described by tunes of the Pythia Monte Carlo generator\cite{11,12} based on charged particle spectra in the central region, especially for the minimum bias sample. The energy flow observables discussed in \cite{16}, on the other hand, can serve to investigate features of events that depend on (semi)hard color radiation. For proposed studies of forward event shapes and correlations to investigate minimum bias, see \cite{19}.

Ref.\cite{16} selects forward and central jets according to the cuts
\begin{equation}
1 < \eta_c < 2, \quad -5 < \eta_f < -4
\end{equation}
where $\eta_c$ and $\eta_f$ are the central and forward jet pseudorapidities. It considers the associated transverse energy flow as a function of pseudorapidity
\begin{equation}
\frac{dE_\perp}{d\eta} = \frac{1}{\sigma} \int dq_\perp q_\perp \frac{d\sigma}{dq_\perp} d\eta.
\end{equation}
The energy flow is sensitive to color radiation associated with the trigger specified in Eq. (1). We observe that the transverse factor $q_\perp$ in the integrand on the right hand side in Eq. (2) enhances the sensitivity to the high momentum transfer end of the QCD parton cascades compared to the inclusive jet cross sections. On one hand, it makes the transverse momentum ordering approximation less physically justified in the long-time evolution of the parton cascade. On the other hand, it increases the importance of corrections due to extra hard-parton emission in the jet production subprocess at the shortest time scales.

The energy flow can be analyzed by employing the approach suggested in \cite{14}, in which one couples the short distance forward-jet matrix elements\cite{8}, which contain extra hard-gluon emission via high-energy factorization\cite{7}, to the transverse-momentum dependent parton showers\cite{20,21}, which go beyond the collinear ordering approximation by implementing CCFM evolution in the Cascade Monte Carlo. (See \cite{22} for a study of phenomenological implications of this dynamics on multi-jet final states.) In addition to radiative corrections from multiple emission in a single parton chain, the evaluation of $dE_\perp/d\eta$ is sensitive to possible contributions of multiple parton chains. See \cite{16} for discussion of this.

Fig. 1 shows the transverse energy flow in the inter-jet region for the cases of particle flow and of minijet flow\cite{16}. Besides the calculation described above, given by the curves labelled Cascade, we report results obtained from Pythia\cite{12} and Powheg\cite{23} Monte Carlo event generators. Pythia\cite{12} is used in two different modes, with multiple parton interactions (Pythia-mpi, tune Z2\cite{24}) and without multiple parton interactions (Pythia-nompi). The particle energy flow plot on the left in Fig. 1 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 minijet energy flow plot on the right in Fig. 1 indicates similar effects, with reduced sensitivity to infrared radiation. These results are of interest for the QCD tuning of Monte Carlo generators, especially in connection with the estimation of QCD backgrounds in search channels involving two jets far apart in rapidity such as Higgs boson searches from vector boson fusion\cite{25,26}.

Ref.\cite{16} also examines the energy flow in the outside region corresponding to rapidities opposite to the forward jet, far in the backward region. In this region one finds a suppression of the transverse flow, due to phase space, from single-shower calculations. Here one is sampling contributions from the initial-state decay chain at substantially larger values of longitudinal momenta, where the effects of corrections to collinear ordering, taken into account by the Cascade result, are not large. On the other hand, contributions from multiple showers are significant\cite{16} due to gluon radiation shifting to larger values of $x$ in each of the sequential parton chains, as the total energy available to the collision is shared between the different chains.
Figure 1: Transverse energy flow in the inter-jet region: (left) particle flow; (right) minijet flow.

Note that the analysis discussed in [11,16] can be extended to the case of forward-backward jets. Here one can look for Mueller-Navelet effects [11,16]. Investigating QCD radiation associated with forward-backward jets will serve to analyze backgrounds in Higgs searches from vector boson fusion channels [26] and studies based on a central jet veto [27] to extract information on Higgs couplings [25]. In this case too the underlying jet activity accompanying the Higgs may receive comparable contributions from finite-angle radiative contributions to single-chain showers, extending across the whole rapidity range, and from multiple-parton interactions.

Our focus in this article has been on initial state radiation effects in energy flow observables, relevant to studies of initial-state distributions that generalize ordinary parton distributions [29,30,31] to more exclusive descriptions of event structure. It will be relevant to also investigate final-state effects such as those in [32,33,34], associated with emission of color in restricted phase space regions and depending on the algorithms used to reconstruct the jets.

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