Multijet production at HERA

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Abstract. Multijet production in deep inelastic $ep$ scattering and in photoproduction at HERA is a good testing ground for the limit of validity of diverse aspects of perturbative quantum chromodynamics (pQCD). This publication reports on the latest multijet results at HERA. Studies on parton dynamics at low Bjorken-$x$, underlying gauge-group structure and multiparton interactions based on HERA I multijet data are presented. Tests of the electroweak sector of the Standard Model are also reported: first measurements of multijet charged current deep inelastic scattering with longitudinally-polarised electron beams at HERA are presented.

1. Multijet production at low $x_{Bj}$

Parton dynamics in $ep$ scattering at HERA is well described in the DGLAP formalism at intermediate and high values of Bjorken-$x$ ($x_{Bj}$) and photon virtuality, $Q^2$. At low values of $x_{Bj}$ DGLAP evolution is expected to breakdown. Evidence for this effect is searched for [1, 2] by studying multijet cross sections at low-$x_{Bj}$ and $Q^2$. Within the DGLAP approach, only $k_T$-ordered parton emissions are considered. Therefore, deviations from QCD predictions may indicate the need of an alternative approach such as the BFKL, which accounts for non-ordered parton emissions. At low-$x_{Bj}$, the transverse momenta and angular correlations between partons produced in the hard scatter, ultimately observed in the jets, may also be sensitive to effects beyond DGLAP dynamics.

Inclusive dijet and trijet production in deep inelastic $ep$ scattering were measured by ZEUS for $10 < Q^2 < 100$ GeV$^2$ and $10^{-4} < x_{Bj} < 10^{-2}$, and trijet production was measured by H1 for $5 < Q^2 < 80$ GeV$^2$. Jets were identified in the hadronic centre-of-mass (HCM) frame using the $k_T$ cluster algorithm in the longitudinally invariant inclusive mode.

The measured cross sections, presented in Fig. 1 as a function of $x_{Bj}$, were compared to order $\alpha_S^2$ and $\alpha_S^3$ QCD predictions. The O($\alpha_S^2$) calculation underestimates the data, but the O($\alpha_S^3$) predictions are closer to the data, showing no evidence for DGLAP breakdown. The only exception is seen in the lowest $x_{Bj}$ bin of Fig. 1, where the trijet cross section is still underestimated by the O($\alpha_S^3$) calculation.

Multi-differential cross sections as functions of the jet transverse momenta, azimuthal angles, and pseudorapidity correlations were also measured by ZEUS, and compared with QCD predictions. The cross section for dijet production is presented in Fig. 2 as a function of $\sum |p_{T,HCM}|$, the transverse component of the vector sum of the two jet momenta with the highest HCM $E_T$. The data is well described by the O($\alpha_S^3$) predictions in the whole measured range, both for dijet and trijet production. Within the theoretical uncertainties, DGLAP dynamics describes the data, provided that higher-order corrections (O($\alpha_S^3$)) are considered.
2. Multijet production in charged current DIS

The electroweak sector of the Standard Model was studied in multijet final states by ZEUS [3]. Jet production in charged-current (CC) deep inelastic scattering proceeds, at leading order (LO), via the quark-parton model \((Wq \rightarrow q)\), the QCD-Compton \((Wq \rightarrow qg)\) and W-gluon fusion \((Wg \rightarrow q\bar{q})\) processes. Thus, CC DIS is sensitive to both \(\alpha_S\) and \(M_W\).

Inclusive, dijet and trijet production in CC processes were measured with the ZEUS detector in \(ep\) DIS in the laboratory frame. The data were taken during the 2004-2006 running period when HERA operated with polarised electron beams. The kinematic region for the measurement is given by \(Q^2 > 200\) GeV\(^2\), \(y < 0.9\), and the following jet requirements: for the inclusive-jet sample, at least one jet with \(E_{T}^{jet} > 14\) GeV; for the dijet, sample one additional jet with \(E_{T}^{jet} > 5\) GeV and for the three jet sample, a third jet with \(E_{T}^{jet} > 5\) GeV. All jets were also required to have \(-1 < \eta_{jet} < 2.5\).

Inclusive-jet production was studied in samples of positive and negative longitudinally polarised electron beams, with a luminosity-weighted average polarisation for each case of \(P = +0.30\) and \(P = -0.27\), respectively. The measured negatively and positively polarised cross sections are shown in Fig. 3 as a function of \(Q^2\). The bottom plot shows the ratio of both cross sections. The data are compared to LO Monte Carlo prediction, based on the Colour Dipole Model (CDM). The data are well described by the prediction. The ratio of the negatively- to positively-polarised cross sections are in good agreement with the Standard Model. The same observations are true for the cross sections and ratios as functions of \(E_{T}^{jet}\), \(\eta_{jet}\) and \(x_{BJ}\).

The unpolarised-corrected cross sections were compared to the predictions of CDM Monte Carlo. For the inclusive jets, the predictions give a reasonable description of the \(\eta_{jet}\) distribution, as well as \(Q^2\) and \(x_{BJ}\). The dijet and trijet unpolarised cross sections are also reasonably well described by the predictions of CDM.

3. Angular correlations in multijet production in DIS

The underlying gauge structure of the theory of strong interactions can be studied using angular correlations in multijet processes. The predictions of different colour configurations have been compared to data with three jets in the final state. The shapes of the trijet cross sections as a function of various angular variables can in principle differentiate the contributions from the different colour configurations.

The variables studied are the angle between the plane determined by the highest transverse energy jet and the beam and the plane determined by the two lowest transverse energy jets; the angle between the two lowest transverse energy jets; the angle \(\beta_{KSW}\) defined by \(\cos(\beta_{KSW}) = \cos[1/2(\angle[\vec{p}_1 \times \vec{p}_B],(\vec{p}_2 \times \vec{p}_B)] + \angle[(\vec{p}_1 \times \vec{p}_B), (\vec{p}_2 \times \vec{p}_3)]\), where the \(\vec{p}_i\) is the momentum of the jet \(i\) and \(\vec{p}_B\) a unit vector in the beam direction; and \(\eta_{jet}^{max}\) which is the maximum pseudorapidity of the three jets with highest transverse energy.

Trijets were measured [4] with the ZEUS detector in neutral current DIS as a function of these variables. Jets were identified using the \(k_T\) cluster algorithm in the longitudinally invariant inclusive mode in the Breit frame. The measurements were compared to fixed-order perturbative calculations assuming the values of the colour factors \(C_F\), \(C_A\) and \(T_F\) as derived from a variety of gauge groups. The data disfavour the predictions based on the gauge groups with \(T_F/C_F \approx 0\) (as predicted by SU(N), large N) or \(C_F=0\), but do not have enough estastistical power to distinguish between the gauge groups SU(3) and U(1)\(^3\). The data are consistent with the admixture of colour configurations as predicted by SU(3).

4. Multiparton interactions

4.1. Mini-jets in DIS

In \(ep\) collisions, if the transverse moment \(p_T\) of the interacting partons is larger than \(Q^2\), the partonic content of the exchanged virtual photon may be resolved. In this case, the photon
will behave as a hadron-like object, and its scattering off a proton may involve more than one parton interaction. Evidence for multiparton interactions (MPIs) was searched for in DIS for the first time [5] with the H1 detector in events containing low transverse momenta jet (mini-jets). For this study, two data samples, an inclusive-jet and a dijet samples, were collected during 1999-2000.

In the inclusive-jet sample, a jet with the highest transverse momenta is identified as the leading jet and its axis defines the azimuthal angle $\Delta \Phi^* = 0$. Most of the activity due to the primary partons interaction is expected to occur in the region around $|\Delta \Phi^*| = 60^\circ$, the “toward region”. Other activity regions defined with respect to the jet axis are the two back-to-back transverse regions, $60^\circ < |\Delta \Phi| < 120^\circ$, and the “away region”, $|\Delta \Phi| > 140^\circ$. Similarly, in the dijet sample, the detector is divided in activity regions, with the requirement that a sub-leading jet is contained within the “away region”. For each event, the transverse regions are further selected as the “high activity”, where contributions from initial- and final-state radiation are expected to happen, and the “low activity region”. Beam remnant and multiparton interactions should, in first approximation, be independent of the primary hard scattering. Thus, such interactions could be seen in any of the regions, but due to the above considerations, they will be more visible in the “low activity region”.

In a sample of DIS events with $5 < Q^2 < 100$ GeV$^2$ and $0.1 < y < 0.7$, leading and sub-leading jets were required to have $P_T > 5$ GeV and $-1.7 < \eta < 2.79$. Moreover mini-jets were selected using the same algorithm and $\eta$ cut as the hard jets, but with $P_T > 3$ GeV.

Mini-jet multiplicities were measured as a function of $p_T$ of the leading jet for the four activity regions defined above, in three bins of $Q^2$. The results are compared to various QCD based models. The results for the inclusive-jet sample are presented in Fig. 4, compared with PYTHIA MC with and without MPIs. In the toward and away regions, both MC with and without MPIs give a good description of the data. For the agreement with the data in the high and low activity regions, it is crucial to add MPIs to the MC models, specially at lower values of $Q^2$. Also, the addition of MPIs to MC models improves the description of the dijet data

4.2. Multijet photoproduction

A similar conclusion was obtained by the ZEUS Collaboration from the study of three- and four-jet final states in photoproduction [6]. The three- and four-jet measured cross sections have been compared to leading-logarithm parton-shower Monte Carlo models, with and without multi-parton interactions. The study was done in two mass regions, $25 < M_{nj} < 50$ GeV and $M_{nj} > 50$ GeV, where $M_{nj}$ is the invariant mass of the n-jet system. In the low-mass region, the MC models without MPI underestimate the data. Adding MPI to the MC simulation improved the description of the data. Presently, the multijet photoproduction predictions from pQCD are only available up to $O(\alpha\alpha_s^3)$. Such predictions were compared to the data, and result too low in the low-mass region. A much better agreement with QCD is achieved when MPIs are accounted for.

References
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[4] ZEUS Coll., preprint ZEUS-prel-05-026
[5] H1 Coll., preprint H1prelim-07-032.
[6] ZEUS Coll., S.Chekanov et al,DESY-07-102, published online in Nuclear Physics B.
Figure 1. DIS trijet cross section as a function of $x_{ Bj}$.

Figure 2. DIS trijet cross section as a function of $\sum \vec{p}_{ T,HCM}^2$ at low $x_{ Bj}$.

Figure 3. Dijet cross section as a function of $Q^2$ in charged current DIS, for positive and negative longitudinally polarised $e$ beams.

Figure 4. Mini-jet multiplicities as a function of $p_T$ of the leading jet for the inclusive jet sample.