PROCEEDINGS OF SCIENCE

Jets and subjets at HERA

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The latest results on jets and jet substructure from the ZEUS Collaboration are presented. These measurements allow stringent tests of perturbative QCD and the electroweak sector of the Standard Model. In particular, they provide contraints on the proton parton distribution functions and allow tests of the underlying gauge symmetry, studies of the pattern of parton radiation and tests of the effects of colour coherence.

The 2009 Europhysics Conference on High Energy Physics,
July 16 - 22 2009
Krakow, Poland

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1. Introduction

Jet production and jet substructure have been extensively studied at HERA. The results on jets have proven to be a powerful tool to test perturbative QCD and the electroweak sector of the Standard Model (SM), to constrain the proton parton distribution functions (PDFs), to determine the strong coupling, α_s, and to test the underlying colour dynamics. Jet substructure has been used to test the pattern of parton radiation and the splitting functions, colour-coherence effects and the underlying colour dynamics, as well.

Jet production in neutral (NC) and charged current (CC) deep inelastic ep scattering (DIS) up to order α_s proceeds via the quark-parton model, boson-gluon fusion and QCD Compton processes. For NC, a virtual γ or Z^0 and for CC, a $W^{\pm}$, is emitted by the initial electron or positron, which interacts with a parton in the proton. An electron (for NC) or a neutrino (for CC) is found in the final state together with one or more jets. The jet-production cross section can be written in QCD as the convolution of the parton densities in the proton and the partonic cross section. The DIS processes are characterised by only two of the following kinematic variables: Q^2, the virtuality of the exchanged boson, Bjorken x and the inelasticity y.

2. Jet production in CC DIS

Jets were reconstructed using the k_T cluster algorithm in the laboratory frame in the kinematic range given by $Q^2 > 200$ GeV^2 and $y < 0.9$ [1]. Events with at least one jet of transverse energy, $E_T^{\rm jet}$, in excess of 14 GeV and pseudorapidity, $\eta^{\rm jet}$, in the range between -1 and 2.5 were selected. The measurements correspond to a data sample of 360 pb^{-1} of integrated luminosity. The inclusive-jet cross sections for electron and positron beams were measured as functions of $E_T^{\rm jet}$ (not shown). Both measured cross sections decrease as $E_T^{\rm jet}$ increases; however, the cross section for the positron sample decreases more rapidly than the one for the electron sample. The next-to-leading-order (NLO) QCD predictions describe reasonably well the shape and magnitude of the data. The ratio of the cross sections for electron and positron beams is naively expected to be ≈ 2, since there are twice as many u-quarks as d-quarks in the proton. However, this naive picture gets modified by the x dependence of the PDFs; the measured ratio is observed to increase as $E_T^{\rm jet}$ increases, in agreement with the QCD predictions. This has been studied in more detail by measuring the inclusive-jet cross section as a function of x (see Fig. 1). The cross section for electron (positron) beams is sensitive to the u (d)-quark density. The NLO QCD calculations give a good description of the data. Figure 1 also shows the theoretical uncertainties, clearly dominated by the PDF uncertainty specially for positron beams at high x. Therefore, these measurements have the potential to constrain further the valence-quark PDFs when included in global fits.

During the HERA II running period, longitudinally-polarised electron and positron beams were available. This allowed the test of the SM prediction for polarised cross sections: a linear dependence of the CC cross section with polarisation is expected and the right (left)-handed electron (positron) cross section vanishes due to the chiral nature of the weak interaction. The inclusive-jet cross sections for electrons and positrons beams with different longitudinal polarisations were measured as functions of Q^2 (not shown). The predictions of the SM are in good agreement with the data.

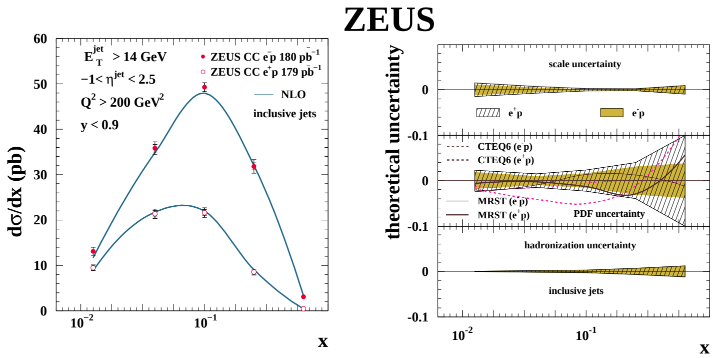

Figure 1: Inclusive-jet cross sections as functions of x in CC DIS.

Multijet production in CC DIS provides a test of QCD directly beyond leading order (LO). More than two jets can appear in the final state due to gluon emission or splitting. The cross sections as functions of the dijet, $M^{\rm jj}$, or three-jet, $M^{\rm 3j}$, invariant mass were measured separately for electron and positron beams (not shown). The QCD predictions for $M^{\rm 3j}$ describe well the shape of the data; however, the predictions for $M^{\rm jj}$ tend to be below the data at high $M^{\rm jj}$ values. This constitutes the first observation of three-jet events in CC interactions. Furthermore, a small number of four-jet events was observed.

3. Angular correlations in three-jet events

The colour factors C_F, C_A and T_F, which are related to the strength of gluon emission, gluon splitting into a gg pair and gluon splitting into $q\bar{q}$ pair, respectively, are given by the underlying gauge-group structure and so their measurement provides direct access to the symmetry group. Since the qqg and ggg couplings have different spin structures, the colour factors give rise to a specific pattern of angular correlations between the final-state jets. At HERA, it is possible to test the underlying gauge symmetry by studying angular correlations in three-jet events. The four diagrams in Fig. 2 represent the main colour configurations expected in NC DIS at HERA. The three-jet production cross section can be expressed in terms of the colour factors as $\sigma_{ep\to 3\rm jets} = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$. Variables have been designed [2] to highlight the contributions from the different colour configurations: θ_H, the angle between the plane determined by the highest-$E_T^{\rm jet}$ jet and the beam and the plane determined by the two lowest-$E_T^{\rm jet}$ jets; α_{23}, the angle between the two lowest-$E_T^{\rm jet}$ jets; $\beta_{\rm KSW}$, defined by $\cos\beta_{\rm KSW} = \cos\frac{1}{2}[\angle[(\vec{p}_1\times\vec{p}_3),(\vec{p}_2\times\vec{p}_B)] + \angle[(\vec{p}_1\times\vec{p}_B),(\vec{p}_2\times\vec{p}_3)]]$; and $\eta_{\rm max}^{\rm jet}$, the pseudorapidity of the most forward jet.

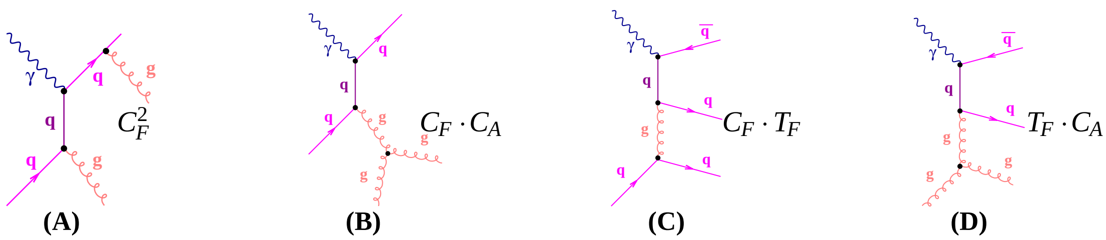

Figure 2: Examples of diagrams in NC DIS three-jet events for different colour configurations.

Three-jet events in NC DIS have been selected using the k_T cluster algorithm in the Breit frame in the kinematic range given by $Q^2 > 125$ GeV^2. The $\mathcal{O}(\alpha_s^2)$ predictions for the different colour

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configurations show that the distribution for σ_B has a very distinct shape for all variables. The distribution for σ_D presents a different shape than the other configurations for the $\eta^{\rm jet}_{\rm max}$ variable. QCD, based on the SU(3) gauge group, predicts a 23%, 13%, 39% and 25% contribution for σ_A, σ_B, σ_C and σ_D, respectively, in the selected region of phase space.

Figure 3 shows the measured normalised three-jet cross sections in NC DIS as functions of the angular-correlations variables compared with the $\mathcal{O}(\alpha_s^2)$ predictions based on different symmetry groups. The data disfavour the predictions based on the symmetry group SU(N), in the limit of large N, and $C_F = 0$. The difference in the predictions based on SU(3) and U(1)^3 are of the same order as the uncertainties in the data. The measurements are consistent with the admixture of colour configurations as predicted by SU(3). There are some discrepancies between data and theory which can be attributed to higher-order contributions: the $\mathcal{O}(\alpha_s^3)$ predictions based on SU(3) give a very good description of the data (not shown). Therefore, these measurements have the potential to be useful in the extraction of the colour factors in hadronic-like reactions.

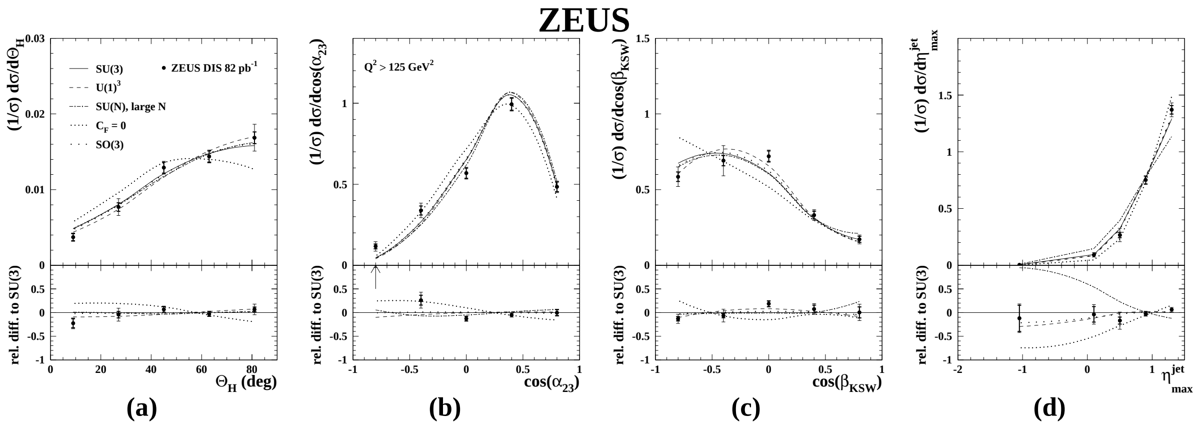

Figure 3: Normalised three-jet cross sections in NC DIS as functions of (a) θ_H, (b) α_{23}, (c) $\beta_{\rm KSW}$ and (d) $\eta^{\rm jet}_{\rm max}$.

4. Subjet distributions

Subjets are jet-like substructures identified by reapplying the k_T algorithm on the particles belonging to a jet at smaller values of the resolution parameter, $y_{\rm cut}$. Subjets can be used to study the pattern of parton radiation and to test colour-coherence effects. The pattern of parton radiation from a primary parton is dictated in QCD by the splitting functions and, therefore, the measurements provide a direct test of these functions and their scale dependence. QCD predicts that soft gluon radiation tends to be emitted towards the proton direction. Measurements of two-subjet distributions were performed [3] as functions of the fractional subjet transverse energy, $E_T^{\rm sbj}/E_T^{\rm jet}$, the difference between the pseudorapidity (azimuth) of the subjet with respect to that of the jet, $\eta^{\rm sbj} - \eta^{\rm jet}$ ($|\phi^{\rm sbj} - \phi^{\rm jet}|$), and $\alpha^{\rm sbj}$, the angle which forms the highest-$E_T^{\rm sbj}$ subjet in the $\eta - \phi$ plane with the beam line as viewed from the jet centre. The cross sections were measured for those jets which contained exactly two subjets at $y_{\rm cut} = 0.05$. Furthermore, measurements of three-subjet distributions were made [4] for those jets which contained exactly three subjets at $y_{\rm cut} = 0.03$.

Figure 4a shows the normalised two-subjet cross sections as functions of $E_T^{\rm sbj}/E_T^{\rm jet}$, $\eta^{\rm sbj} - \eta^{\rm jet}$, $|\phi^{\rm sbj} - \phi^{\rm jet}|$ and $\alpha^{\rm sbj}$. The measurements show that the two subjets tend to have similar transverse

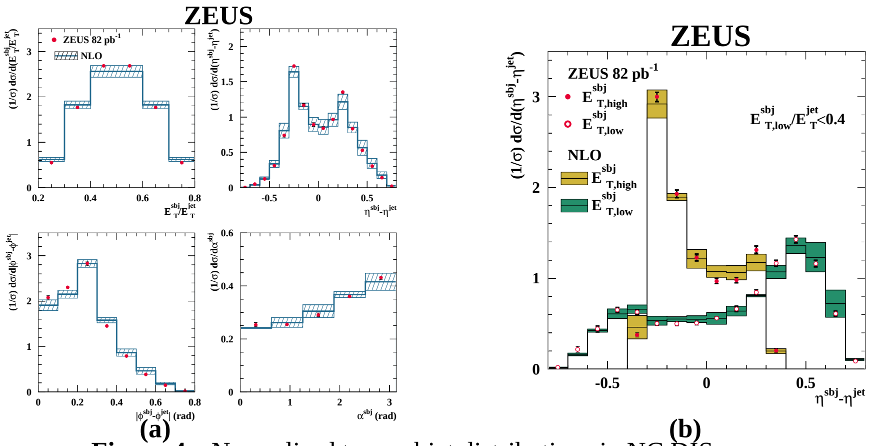

Figure 4: Normalised two-subjet distributions in NC DIS.

energies. The distribution in $\eta^{\rm sbj} - \eta^{\rm jet}$ has a two-peak structure. The cross section as a function of $|\phi^{\rm sbj} - \phi^{\rm jet}|$ shows a suppression around $|\phi^{\rm sbj} - \phi^{\rm jet}| = 0$, which comes from the fact that the two subjets cannot be resolved when they are too close together. This is also observed in the dip between the two peaks in $\eta^{\rm sbj} - \eta^{\rm jet}$. The $\alpha^{\rm sbj}$ distribution shows that the highest-$E_T^{\rm sbj}$ subjet tends to be in the electron-beam direction. This is consistent with the asymmetric two peak structure observed in $\eta^{\rm sbj} - \eta^{\rm jet}$ and in agreement with the expectation from colour-coherence effects. NLO QCD predictions, which contain the contributions for quark and gluon splitting, are compared to the data in Fig. 4a and give an adequate description of the measured distributions. Similar measurements were performed for the three-subjet sample (not shown). Analogous conclusions to those for the two-subjet cross sections can also be drawn from these measurements. To study in more detail the colour-coherence effects, the two-subjet cross section as a function of $\eta^{\rm sbj} - \eta^{\rm jet}$ has been measured for those jets with subjets of different transverse energies ($E_{T,\rm low}^{\rm sbj}/E_T^{\rm jet} < 0.4$), separately for the lower and the higher-$E_T^{\rm sbj}$ subjet (see Fig. 4b). The measurements show that the higher-$E_T^{\rm sbj}$ subjet tends to be in the electron-beam direction whereas the lower-$E_T^{\rm sbj}$ subjet tends to be emitted in the proton-beam direction. The NLO predictions describe the data well. This behaviour, also observed in the three-subjet sample, can be attributed to colour-coherence effects between the initial and final states, and indicates that soft gluon radiation is indeed emitted predominantly towards the proton direction.

Angular correlations between the three subjets are also sensitive to the underlying gauge symmetry. Measurements of normalised three-subjet distributions were performed as functions of variables sensitive to the colour configurations: α_{23}, the angle between the two lowest-$E_T^{\rm sbj}$ subjets as seen from the jet centre in the $\eta - \phi$ plane, and γ, the angle between the highest-$E_T^{\rm sbj}$ subjet and the vector difference of the two lowest-$E_T^{\rm sbj}$ subjets as seen from the jet centre in the $\eta - \phi$ plane. For these observables, the configurations proportional to C_A display a very distinct behaviour (see Fig. 5a and 5b). Figures 5c and 5d show the measured normalised three-subjet cross sections in NC DIS compared with the $\mathcal{O}(\alpha_s^2)$ predictions based on SU(3). The measurements are consistent with the admixture of colour configurations as predicted by SU(3). QCD predicts a 47%, 17%, 27% and 9% contribution for σ_A, σ_B, σ_C and σ_D, respectively, in the selected region of phase space. Therefore, these measurements also have the potential to be useful in the extraction of the colour factors in hadronic-like reactions.

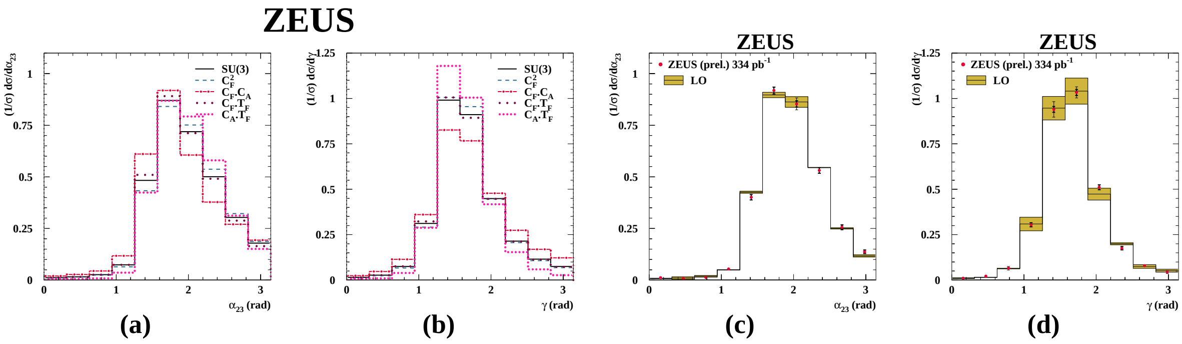

Figure 5: Predicted $\mathcal{O}(\alpha_s^2)$ three-subjet normalised cross sections as functions of (a) α_{23} and (b) γ. Measurements of the normalised three-subjet cross sections in NC DIS as functions of (c) α_{23} and (d) γ.

5. Conclusions

Jet production and jet substructure are still being extensively studied at HERA. The latest results from multijet production in CC DIS, angular correlations in three-jet events and two- and three-subjet distributions in NC DIS have been presented. These measurements allowed stringent tests of pQCD and the electroweak sector of the SM. In particular, they provide contraints on the proton PDFs and allow tests of the underlying gauge symmetry, studies of the pattern of parton radiation and tests of the effects of colour coherence. As the main conclusion of these studies, jet measurements at HERA represent a very powerful tool that provides stringent tests of the theory.

References

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