Tests of the Standard Model in jet production at HERA

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Abstract
Measurements of the differential cross sections for inclusive jet production in neutral-current (NC) deep inelastic e^+p scattering (DIS) at high Q^2 (where Q^2 is the virtuality of the exchanged boson) show no significant deviation from Standard Model expectations up to the highest jet transverse energies studied, $E_T^{jet} \sim 85$ GeV. First measurements of three-jet production in NC DIS have been made in a wide range of Q^2. The measured topological distributions for three-jet production are in agreement with the pattern of parton radiation in QCD.

Inclusive jet measurements. At high Q^2 and high values of the Bjorken-x variable (x_{Bj}), both the H1 and ZEUS collaborations reported [1] an excess of events from NC e^+p interactions with respect to the expectations of the Standard Model (SM). These observations have prompted considerable discussion in the particle physics community as possible evidence for anomalies in the parton momentum distributions of the proton or of physics beyond the SM.

New particles or resonances that decay into e^+ + jet(s) would lead to deviations in the differential cross sections for inclusive jet production in NC DIS with respect to the expectations of the SM. A narrow resonance in e^+-jet would show up as a Jacobean peak in the differential cross section as a function of E_T^{jet} in the laboratory frame. In NC DIS at high Q^2 the most probable final state in the SM consists of a single jet balancing the positron's transverse momentum, $E_T^{jet} \sim Q$. A resonance decaying into e^+ plus several jets would populate the region $E_T^{jet} \ll Q$, where multijet production in the SM is suppressed by higher powers of the strong coupling constant (α_s).

Measurements of the inclusive differential jet cross section as a function of E_T^{jet} in NC DIS at high Q^2 are reported here. The data sample used in this analysis [2] was collected with the ZEUS detector at the ep collider HERA and corresponds to an integrated luminosity of 43 pb^{-1}. During 1995-1997 HERA operated with positrons of energy $E_e = 27.5$ GeV colliding with protons of energy $E_p = 820$ GeV. Events from NC DIS interactions are selected by requiring an isolated positron with energy in excess of 10 GeV. The event sample is restricted to the kinematic range $Q^2 > 125$ GeV^2 . Jets are searched for in the pseudorapidity‡ (η) - azimuth (φ) plane of the laboratory frame using the longitudinally invariant k_T-cluster algorithm in the inclusive mode [3]. The axis of the jet is defined according to the Snowmass convention [4], where η^{jet} (φ^{jet}) is the transverse-energy weighted mean pseudorapidity (azimuth) of all the particles belonging to that jet. The jets have been reconstructed using the uranium-scintillator calorimeter (CAL) and corrected for detector effects to yield jets of hadrons.

The cross section $d\sigma/dE_T^{jet}$ has been measured in the E_T^{jet} range between 14 GeV and 85 GeV integrated over $-1 < \eta^{jet} < 2$ for $Q^2 > 125$, 500, 1000 and 2000 GeV^2. The results are presented in figure 1. The statistical errors are indicated as thick error bars. The systematic uncertainties not associated with the absolute energy scale of the CAL in the data have been added in quadrature to the statistical errors and are shown as thin error bars. The dominant source of systematic error ($\sim 10\%$) is due to the uncertainty on the absolute energy scale of the CAL ($\pm 3\%$) in the data and is

‡ The pseudorapidity is defined as $\eta = -\ln(\tan\frac{\theta}{2})$, where the polar angle θ is taken with respect to the proton beam direction.

shown as a shaded band. The measured $d\sigma/dE_T^{jet}$ for $Q^2 > 125$ GeV^2 exhibits a steep fall-off of 4 orders of magnitude in the E_T^{jet} range considered.

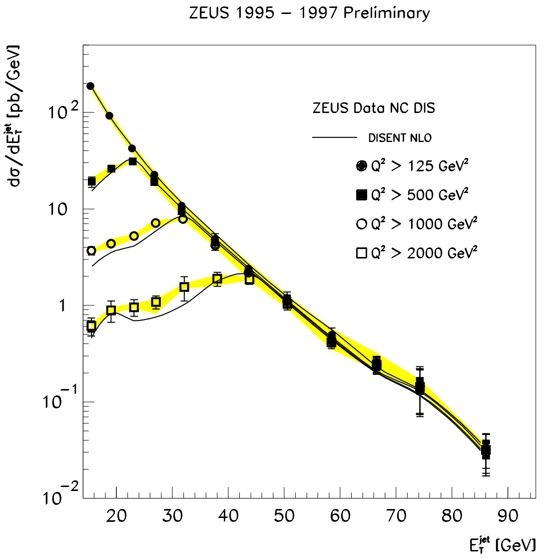

Figure 1. ZEUS inclusive jet cross sections as a function of E_T^{jet}. NLO QCD calculations are shown for comparison.

The measurements in figure 1 have been compared with next-to-leading order (NLO) QCD calculations using the program DISENT [5]. The CTEQ4M [6] proton parton distributions have been used and the renormalisation and factorisation scales have been chosen equal to Q. The calculations are for jets of partons identified by the same jet algorithm as for the data. At present, the DISENT program includes only γ exchange and does not contain QED radiative corrections. In order to compare with the data, the calculations have been supplemented for Z°-exchange and electroweak radiative effects. The correction for these effects depends upon E_T^{jet} and Q^2, and is typically within $\pm 10\%$. The NLO QCD calculations refer to jets of partons whereas the measurements refer to jets at the hadron level. An estimate of the effects of hadronisation has been obtained by comparing the cross sections for jets of hadrons and jets of partons calculated with the DJANGO program [7]. The ratio $(d\sigma/dE_T^{jet}[\text{hadrons}])/(d\sigma/dE_T^{jet}[\text{partons}])$ is relatively constant as a function of E_T^{jet} and within $\pm 5\%$ of unity. The NLO QCD calculations give a good description of the measured $d\sigma/dE_T^{jet}$ with $Q^2 > 125$ GeV^2, both in shape and magnitude. For higher thresholds in Q^2, the NLO QCD calculations reproduce the measured $d\sigma/dE_T^{jet}$ except for $Q^2 > 1000$ GeV^2 in the low-E_T^{jet} region, where the data are above the calculations. However, the NLO QCD correction at $E_T^{jet} \sim 20$ GeV for $Q^2 > 1000$ GeV^2 increases the cross section by 50% and suggests that higher-order QCD corrections can be very large. To assess the origin of this possible discrepancy, improved QCD calculations are needed. Otherwise no significant deviations are observed.

Three-jet production. Measurements of three-jet cross sections provide tests of perturbative QCD at higher orders [8] than in inclusive jet production. In particular, the pattern of parton radiation can be investigated in detail by means of topological distributions.

The H1 collaboration has measured for the first time [9] the differential cross sections for three-jet production in NC DIS using an integrated luminosity of 33 pb^{-1}. The jets are defined in the Breit frame§, where the virtual photon collides head-on with the proton, using the longitudinally invariant k_T-cluster algorithm in the inclusive mode. The recombination of the particles is done according to the Snowmass convention. Each jet is required to have $E_T^{jet}(\text{Breit}) > 5$ GeV and $-1 < \eta^{jet}(\text{lab}) < 2.5$. Events with at least three jets are selected and a cut on the three-jet invariant mass is applied, $M_{3\text{jet}} > 25$ GeV. The data have been corrected for detector effects and QED radiation from the lepton line.

The differential cross section $d\sigma/dQ^2$ for three-jet production has been measured in the range $5 < Q^2 < 5000$ GeV^2. The results (dots) are presented in figure 2, where the inner error bars indicate the statistical uncertainties. The systematic uncertainties have been added in quadrature to the statistical errors and the results are shown as the outer error bars. The measured cross section exhibits a steep fall-off of four orders of magnitude in the measured range. A leading-order (LO) QCD calculation, which is $\mathcal{O}(\alpha_s^2)$ for three-parton final states, using the program DISENT, is compared to the data in figure 2. Hadronisation effects are estimated to lower the cross section by about 20-40%. The calculation provides a fair description of the data except in the low-Q^2 region ($Q^2 < 40$ GeV^2).

The topology of three-jet events has been studied in their centre-of-mass system using the following variables: a) the scaled jet energies $X_3 = 2E_3/M_{3\text{jet}}$ and $X_4 = 2E_4/M_{3\text{jet}}$, where the outgoing jets are

§ The Breit frame is defined by $\vec{q} + 2x_{Bj}\vec{P} = \vec{0}$, where $\vec{q}$ and $\vec{P}$ are the momenta of the exchanged boson and the incoming proton.

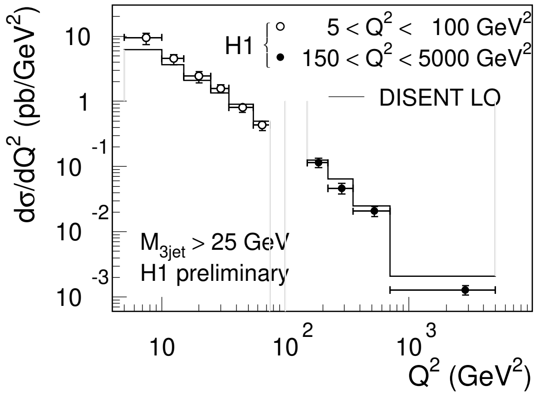

Figure 2. H1 inclusive three-jet cross section as a function of Q^2. A LO QCD calculation is shown for comparison.

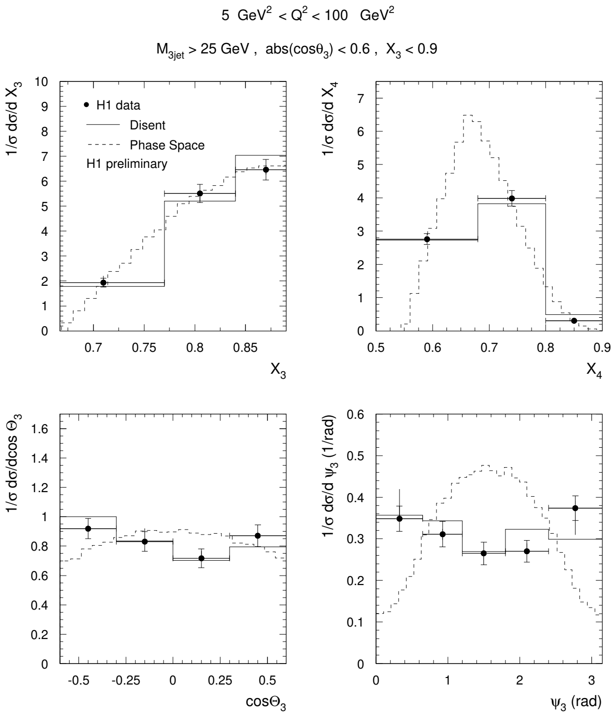

Figure 3. H1 measurements of the three-jet topological distributions. LO QCD calculations (solid histograms) and phase-space predictions (dashed histograms) are shown for comparison.

labelled (3,4,5) and ordered according to decreasing energies ($E_3 > E_4 > E_5$); b) the polar angle of the most energetic jet (θ_3); and c) the angle between the three-jet plane and the plane containing the proton-beam direction and the leading jet (Ψ_3). To remove any bias introduced by the requirements on the jets as completely as possible, the following cuts have been applied: $|\cos\theta_3| < 0.6$ and $X_3 < 0.9$. The measurement of the topological distributions for $5 < Q^2 < 100$ GeV^2 are shown in figure 3. The LO QCD calculations describe the shape of the measured distributions well. These distributions are less affected by hadronisation (below 10%) than $d\sigma/dQ^2$. The distribution of Ψ_3 exhibits most clearly the pattern of parton radiation in QCD: the expectation from phase space would be flat, but the jet requirements deplete the regions $\Psi_3 \sim 0$ and π; the data behave in the opposite way and in agreement with QCD, where the initial-state radiation pole gives rise to enhanced parton radiation in the same plane as that spanned by the proton beam and the leading jet (i.e. $\Psi_3 \sim 0$ and π). This result nicely complements similar investigations of the Ψ_3 distribution in $p\bar{p}$ collisions [10] and γp interactions at HERA [11].

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