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Measurement of High E_T Inclusive Jet Production in Deep-Inelastic ep Scattering at High Q^2

H1 Collaboration

Abstract

Inclusive jet production is studied in neutral current deep-inelastic positron-proton scattering at large four momentum transfer squared $Q^2 > 150$ GeV^2 with the H1 detector using a data sample corresponding to an integrated luminosity of 320 pb^{-1} recorded at HERA-II. The inclusive jet cross section normalized to the neutral current deep inelastic scattering (NC DIS) cross section, called also the jet multiplicity is measured as function of Q^2 and of the jet transverse energy in the Breit frame $E_{T,B}$. The measurements are found to be well described by calculations at next-to-leading order (NLO) in perturbative QCD. Finally present preliminary results are compared to recently published results based on 1999-2000 data recorded by H1 detector during the HERA-I period with an integrated luminosity 65.4 pb^{-1}.

1 Introduction

Jet production in neutral current (NC) deep-inelastic scattering (DIS) at HERA provides an important testing ground for Quantum Chromodynamics (QCD). The Born contribution in DIS gives only indirect information on the strong coupling α_s via scaling violations of the proton structure functions and generates no transverse momenta in the Breit frame[1]. In fact partons with transverse momenta are produced in lowest order (LO) in α_s by the QCD-Compton and boson-gluon fusion processes. Jet production in the Breit frame therefore provides direct sensitivity to α_s and allows for a precision test of QCD. Analyses of inclusive jet production in DIS at high four momentum transfer squared Q^2 were previously performed by the H1 and ZEUS collaborations at HERA. The most recently published analyses [3, 4] are based on HERA-I 1999-2000 data. Perturbative QCD (pQCD) calculations supplemented with hadronisation corrections were found to describe the data.

A new measurement of the inclusive jet multiplicities from the H1 collaboration is based on the full HERA-II data sample corresponding to five times the integrated luminosity of the previous H1 analysis [3]. The inclusive jet multiplicity are defined as the ratio of the jet cross section to the NC DIS cross section. It is measured as a function of the hard scales Q^2 and $E_{T,B}$, the transverse jet energy in the Breit frame, in the ranges $150 < Q^2 < 15000$ GeV^2 and $7 < E_{T,B} < 50$ GeV. This observable takes advantage of a partial cancellation of experimental and theoretical uncertainties. The measurements are compared with pQCD predictions at next-to-leading order (NLO). Higher statistics together with improved calibration of the hadronic energy significantly reduce the total experimental uncertainty compared to previous analyses.

2 Event kinematics and selection

The data sample was collected with the H1 detector at HERA in the years 2003 to 2007 (HERA-II). During this period, HERA collided positrons or electrons[2] of energy $E_e = 27.6$ GeV with protons of energy $E_p = 920$ GeV giving a centre-of-mass energy $\sqrt{s} = 319$ GeV. The data sample used in this analysis corresponds to an integrated luminosity of 320 pb^{-1} shared equally between positron and electron periods.

The DIS phase space covered by this analysis is defined by

$$150 < Q^2 < 15000 \text{ GeV}^2 \qquad 0.2 < y < 0.7$$

where y quantifies the inelasticity of the interaction. These two variables are reconstructed from the four momenta of the scattered positron and the hadronic final state particles using the electron-sigma method [1].

The energy of the scattered electron E'_e is required to exceed 11 GeV and to be detected in regions of the calorimeter where the trigger efficiency is above 98%. The z-coordinate[3] of

[1]Breit frame is a frame where the virtual boson and the proton collide head on.

[2]Unless otherwise stated the colliding lepton is called "electron"

[3]H1 uses a right-handed coordinate system with the z-axis along the beam direction, the +z or forward direction being that of the outgoing proton beam.

the event vertex is required to be within ± 35 cm of the average position of the interaction point. This condition reduces contributions of beam induced background and cosmic muons. The total longitudinal energy balance Σ must satisfy $35 < \Sigma = \sum_i (E_i - p_{z,i}) < 65$ GeV, where the sum runs over all detected particles. This requirement reduces the contributions from photo-production and DIS events with strong initial state radiation. Elastic QED Compton and lepton pair production processes are suppressed by rejecting events containing additional isolated electromagnetic deposits and low hadronic activity. The remaining photo-production background is estimated using Monte Carlo simulations and found to be negligible in all Q^2 and $E_{T,B}$ bins.

The jet analysis is performed in the Breit frame. The boost from the laboratory system to the Breit frame is determined by Q^2, y and by the azimuthal angle of the scattered electron ϕ_{Lab}. Particles of the hadronic final state are clustered into jets using the inclusive k_T algorithm [2] with the p_T recombination scheme and with distance parameter $R = 1$ in the $\eta_B - \phi_B$ plane. The cut $-0.8 < \eta_{Lab} < 2.0$ ensures that jets are well contained within the acceptance of the LAr calorimeter, where η_{Lab} is the jet pseudorapidity in the laboratory frame. This cut is more restrictive than in the HERA-I analysis due to harsher background conditions. Every jet with transverse energy in the Breit frame $E_{T,B}$ with $7 < E_{T,B} < 50$ GeV contributes to the inclusive jet cross section, regardless of the jet multiplicity in the event. In total 120000 jets pass the analysis cuts.

3 Cross section definition

Jet multiplicities are defined as the average number of jets within a range of transverse energy $E_{T,B}$ produced in a DIS event with a given Q^2 and y. In this analysis jet multiplicities are summed over the whole y range. Thus, jet multiplicities are the normalized inclusive jet cross section $\sigma_{Ijet,N}$, calculated as the ratio of the double differential inclusive jet cross section $d\sigma^2_{Ijet}/dQ^2 dE_{T,B}$ and the differential NC DIS cross section $d\sigma_{DIS}/dQ^2$ multiplied by the $E_{T,B}$ bin width W_{Et}:

$$\sigma_{Ijet,N} = \frac{d\sigma^2_{Ijet}/dQ^2 dE_{T,B}}{d\sigma_{DIS}/dQ^2} \cdot W_{Et}$$

4 Monte Carlo models and correction procedure

In order to extract the cross sections at hadron level, the experimental data are corrected bin-by-bin for limited detector acceptance and resolution. The correction factors are determined using simulated NC DIS events. The generated events are passed through a detailed simulation of the H1 detector and subjected to the same reconstruction and analysis chain as the data. The following Monte Carlo event generators are used for this purpose: DJANGOH [5] using the Colour Dipole Model as implemented in ARIADNE [6], and RAPGAP [7] using matrix elements matched with parton showers. Both RAPGAP and DJANGOH provide good descriptions of the data in both the inclusive DIS and the inclusive jet samples and so describe well jet multiplicities.

The purity of the jet sample, defined as the fraction of jets reconstructed in a bin which are genuine from that bin on hadron level, is found to be larger than 60% in all analysis bins. The same is observed for the stability defined as the fraction of hadron level jets that start in a bin and are subsequently reconstructed in that bin. A bin-by-bin correction is applied to the raw measured cross sections. Total correction factors, including detector and QED radiation correction, are determined in one step as the ratio of the cross section obtained from particles at hadron non radiative level to the cross section calculated using particles reconstructed in the detector. Arithmetic means of the correction factors determined by RAPGAP and DJANGOH are used, and half of the difference is assigned as the systematic uncertainty due to the sensitivity of the detailed simulation to the MC model. The correction factors deviate typically by less than 20% from unity. In order to merge positron and electron periods, the data are corrected for Z^0 boson exchange using factors estimated by the LEPTO event generator [8]. Nevertheless, since this correction depends only on Q^2, it cancels to the first order in the ratio. Jet multiplicities are calculated and corrected separately for positron and electron periods and then combined.

5 Systematic Uncertainties

Jet multiplicities benefit from the cancellation of some sources of experimental and theoretical errors in comparison with inclusive jet cross section. The experimental systematic uncertainties and their propagation to different observables are discussed below:

- The relative uncertainty of the electron energy calibration varies from 0.7% to 3% and the absolute uncertainity of the polar angle is 1 to 3 mrad, depending on the electron impact in the calorimeter. They mainly affect the event kinematics and thus are expected to cancel in the ratio of cross sections. Nevertheless the electron systematics propagate to the jet cross section through the boost to the Breit frame. This latter effect amounts to a relative error of 1 to 2% on the jet multiplicities value.

- The energy scale uncertainty of the reconstructed hadronic final state is conservatively estimated to be 2%. It is dominated by the uncertainty of the absolute calorimeter calibration. It affects mainly the jet cross section through the calibration of $E_{T,B}$ and, to reduced extent, the DIS cross section through the reconstruction of y. The resulting uncertainty on the jet multiplicities is typically between 1 and 8%.

- The model dependence of the detector correction factors is estimated as described in section 4. For jet multiplicities this systematic error is below 5% in most of the bins and typically 2%.

- The error on the absolute normalization due to the uncertainty of the luminosity measurement $(1-2\%)$ cancels in the normalized cross section.

Statistical errors are appreciably reduced compared to previous HERA-I publications and amount to $1-2\%$ for most of bins. They rise up to 10% in some kinematically disadvantaged regions (high $E_{T,B}$). Finally the overall experimental error, calculated as the quadratic sum of all above contributions, varies between 3 and 10%, with an average value around 6%. The experimental uncertainties are reduced from typically 7% on the inclusive jet cross sections to 6% on the jet multiplicities value.

6 NLO QCD calculations

The QCD prediction for the jet cross section is calculated using the NLOJET++ program [10], which performs the integration of the matrix elements at NLO in the strong coupling, $O(\alpha_s^2)$. The DIS cross section is calculated at $O(\alpha_s)$ with the DISENT package [11]. The strong coupling is taken as $\alpha_s(M_Z) = 0.118$ and is evolved as a function of the renormalisation scale at two loop precision. The calculations are performed in the $\overline{MS}$ scheme for five massless quark flavours. The parton density functions (PDFs) of the proton are taken from the CTEQ6.5M set [9]. The factorisation scale μ_f is taken to be Q and the renormalisation scale μ_r is taken to be the $E_{T,B}$ for the inclusive jet NLO prediction and Q for DIS. Running of the electromagnetic coupling with Q^2 is also taken into account. No QED radiation is included in the calculation since the data are corrected for this effect.

Jet cross-sections are predicted at the parton level using the same jet definition as in the data analysis. For comparison with the data, hadronisation corrections are calculated for each bin as the ratio of the cross section defined at hadron level to the cross section defined at parton level. These correction factors are determined with the same (LO) Monte Carlo event samples from DJANGOH and RAPGAP used to correct the data from detector to hadron level (see 4). The hadronisation correction factors differ typically by less than 10% from unity and agree at the level of 2% between the two Monte Carlo simulations.

The theoretical uncertainties (or error band) given below include an uncertainty for hadronisation and an estimate of the uncertainty due to the neglect of higher orders in the perturbative calculation. The systematic error attributed to the hadronisation correction is taken to be half of the difference between the correction factors obtained using RAPGAP and DJANGOH. The dominant uncertainty is related to the NLO accuracy and is conventionally estimated by a variation of the chosen scales for μ_f and μ_r by factors ranging from 0.5 to 2. In seven out of the 24 bins in Q^2 and E_T the dependence of the pQCD calculation on μ_r is not monotone, i.e. the largest deviation from the central value is found for factors within the range 0.5 to 2. In such cases the difference between maximum and minimum cross sections found in the variation interval is taken, in order not to underestimate the scale dependence. Renormalisation and factorisation scale uncertainities are added in quadrature. The uncertainty originating from the PDFs is also taken into account using the CTEQ6.5M set of parton densities. The propagation of scale and PDF uncertainties to the cross sections is efficiently performed with the FastNLO program [12].

The scale uncertainties for the jet and for the NC DIS cross-sections are assumed to be uncorrelated. Consequently, the scale uncertainty for the ratio is estimated by adding the two contributions in quadrature. If the uncertainties are assumed to be anti correlated, which leads to the largest change, the resulting theory error increases only slightly by a factor of 1.15. Over the whole phase space, the uncertainty due to the renormalisation scale is found to be the dominant source of the theory error.

7 Results

Figure 1 shows the jet multiplicites as a function of Q^2 and fig. 2 as a function of $E_{T,B}$ in different Q^2 bins. Preliminary results measured with the HERA-II data sample (blue solid dots) are compared with the HERA-I published results [3] (black open dots). For comparison, the HERA-I data points were scaled to correct for a phase space difference due to a slightly larger jet pseudorapidity range. The measured cross sections, represented with statistical errors (inner bars) and with total errors (outer bars), are compared to NLO QCD calculations (grey band). The bands show the theoretical uncertainty associated with scales, PDF parameterization and with the hadronisation correction. In addition to the jet multiplicities the lower part of the figure shows the ratio $R = \sigma^{data}_{Ijet,N}/\sigma^{th.}_{Ijet,N}$ represented with the experimental uncertainty normalized to the central theory prediction (error bars). The grey band around R = 1 displays the relative uncertainty of the theoretical calculations.

Figure 1 shows that the average multiplicity of jets produced in the NC DIS interaction increases versus high Q2 where more phase space for jet production is available. For example, at high Q^2 at least 50% of the events are produced with a well defined highly energetic jet within the acceptance, while at low Q^2 only 25%. Moreover fig. 2 shows that the $E_{T,B}$ spectra get harder with increasing Q^2 especially in the region where Q exceeds $E_{T,B}$. In the higher Q^2 bin the production rate is even roughly independent of the jet transverse energy $E_{T,B}$ at least under 30 GeV.

These new preliminary normalised jet cross-sections are compatible, within the experimental errors, with the published H1 data [3]. The improvement of the experimental accuracy due to increased statistics is most visible in high Q^2 and high $E_{T,B}$ regions where the jet production cross section is small. In almost all bins the theoretical uncertainty, dominated by the μ_r scale uncertainty, is significally larger than the total experimental uncertainty dominated by the hadronic energy scale.

8 Summary

Measurements of jet multiplicities in the Breit frame in deep-inelastic electron-proton scattering in the range $150 < Q^2 < 15000$ GeV^2, based on the total HERA-II data, are presented as functions of Q^2 and $E_{T,B}$. They benefit from increased accuracy compared to recently published H1 measurements based on HERA-I data. The two sets of results are compatible and equally well described by NLO QCD calculations within their respective theoretical and experimental uncertainities.

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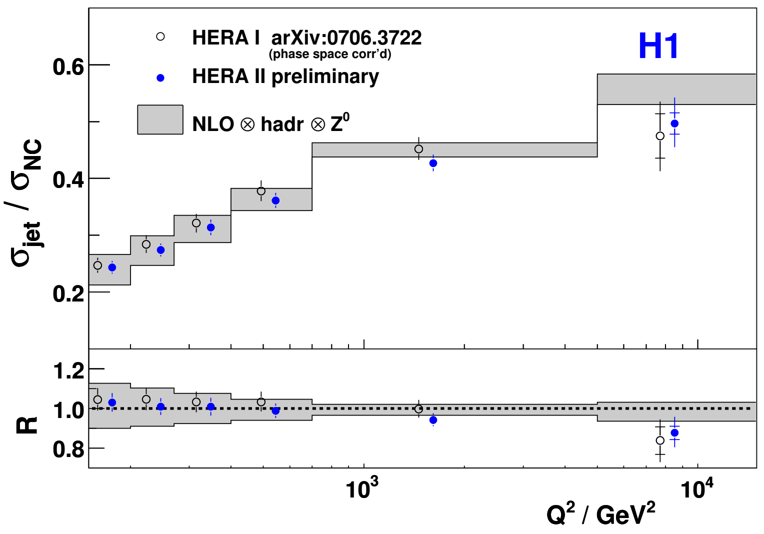

Figure 1: Jet multiplicities as a function of Q^2 measured with HERA-II data compared to HERA-I published data, here shown corrected for phase space. The NLO QCD predictions together with the theory uncertainty are shown as the grey band. The ratio R of data with respect to NLO QCD prediction are shown on the lower plots.

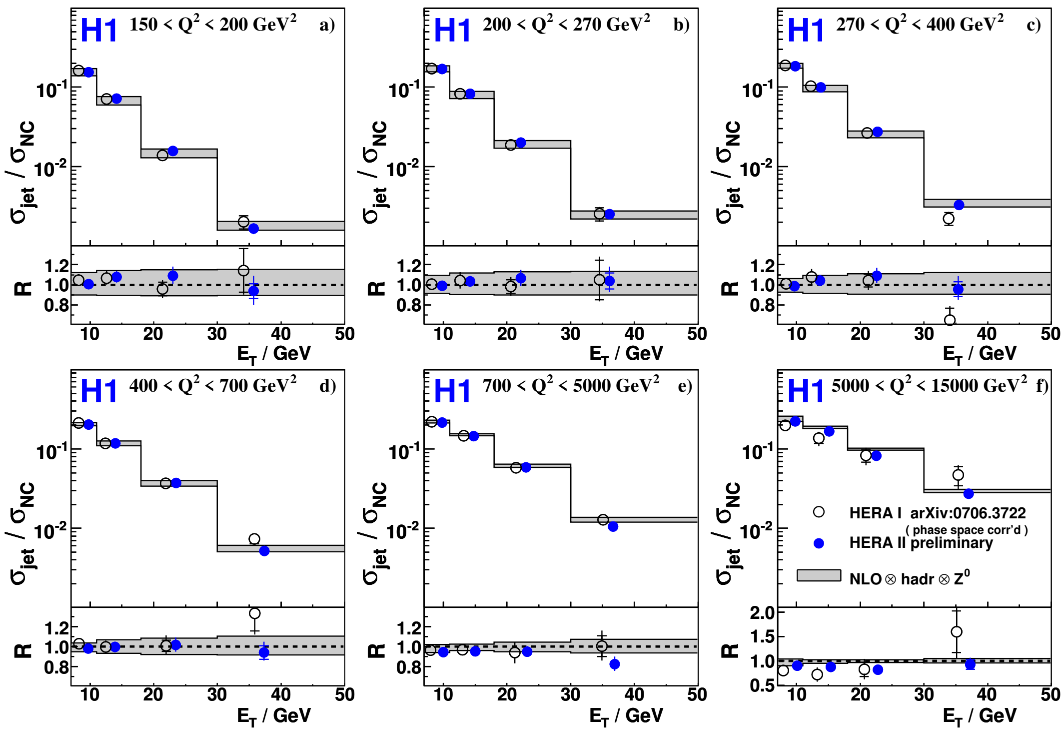

Figure 2: Jet multiplicities as a function of $E_{T,B}$ in regions of Q^2 measured with HERA-II data compared to HERA-I published data, here shown corrected for phase space. The NLO QCD predictions together with the theory uncertainty are shown as the grey band. The ratio R of data with respect to NLO QCD prediction are shown on the lower plots.