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Scaled Charged Particle Momentum Distributions at High Q^2 at HERA

H1 Collaboration

Abstract

The cross-section normalised scaled momentum distribution (x_p) of charged final state hadrons has been measured in DIS ep collisions by H1 at High Q^2 in the Breit frame of reference. Compared with previous results presented by HERA experiments this analysis has significantly higher statistics, extends to higher Q^2, and to the full range of x_p. The results are compared with different models of the fragmentation process as implemented in leading order Monte Carlo models with either parton showers or the colour dipole model of higher order QCD radiation and the string or cluster model for the hadronisation. The results are also compared with an NLO calculation (CYCLOPS).

1 Introduction

In this paper the process of parton fragmentation and hadronisation is studied using the inclusive charged particle spectrum in the current region of the Brit frame of reference in Deep Inelastic Scattering (DIS) data. In the current region of the Breit frame a comparison with one hemisphere of an $\mathrm{e}^+\mathrm{e}^-$ annihilation is possible directly testing quark fragmentation universality. Predictions based on the CYCLOPS [1] program, which combines a next-to-leading order (NLO) perturbative QCD (pQCD) description of DIS with fragmentation functions derived from $\mathrm{e}^+\mathrm{e}^-$ annihilation, are available which allow further tests of quark fragmentation universality, perturbative QCD and factorisation. Predictions of Different models of the parton cascade process (parton showers (PS) [2] and the colour dipole model (CDM) [3]) and of the Hadronisation process (string [4] and cluster [5]) used in leading order matrix element Monte-Carlo programs (RAPGAP [6], DJANGO [7] and HERWIG [8]), which have been tuned to ee results, can be compared to our data.

A particularly suitable frame of reference in which to study quark fragmentation in ep scattering is the Breit Frame [9]. The current region of the Breit frame defines a kinematic area where the properties of the scattered quark can be studied with well defined and relatively clean separation from the proton remnant.

In this frame and within the quark-parton model (QPM) the purely space-like virtual photon has longitudinal momentum $-Q$, where Q is the virtuality of the exchange boson, and collides elastically and head on with a (massless) quark of longitudinal momentum $Q/2$. The struck quark is scattered with an equal but opposite momentum while the proton remnant fragments into the opposite hemisphere.

Hadrons emerging from the interaction with negative longitudinal momenta are assigned to the current region and associated with the struck quark.

The energy scale for the current region, set by the virtual photon, is given by $Q/2$ and, for comparison purposes, is taken to be equivalent to one half of the $\mathrm{e}^+\mathrm{e}^-$ centre of mass energy $E^*/2$ corresponding to one hemisphere.

In the Breit frame the scaled momentum variable x_p is thus defined to be $2p_h^{\pm}/Q$ where $p_h^{\pm}$ is the momentum of a charged track in the current region of the Breit frame. In $\mathrm{e}^+\mathrm{e}^-$ annihilation events the equivalent variable is $2p_h^{\pm}/E^*$.

Previous studies [10, 11, 12, 13, 14] of the scaled momentum spectra (x_p) have shown general agreement between one hemisphere of an $\mathrm{e}^+\mathrm{e}^-$ annihilation interaction when compared with the current region of the Breit frame in ep scattering at high Q. At lower Q this agreement is observed to break down due to higher order QCD processes such as Boson Gluon Fusion (BGF) and Initial state Compton QCD (ICQCD) which can occur before the hard interaction in ep scattering but not in $\mathrm{e}^+\mathrm{e}^-$ annihilation and which can lead to a depletion of the track multiplicity in the current region. Leading order matrix element Monte-Carlo programs, which use models of the parton cascade to describe QCD processes beyond leading order, have been shown to be able to describe the scaled momentum spectra in ep interaction down to low Q.

In this analysis the use of much higher statistics now available at high Q and an improved understanding of the H1 detector and associated systematics provide a much improved measurement of the scaled momenta spectra. Results are now available to $< Q >\sim 100$ GeV, close to the LEP1 centre of mass energy, and to the full range of x_p (nominally, $0 < x_p < 1$).

2 Data Selection

The data used in this analysis were taken by H1 in 2000 when 920 GeV protons were in collision with 27.5GeV positrons and corresponds to an integrated luminosity of $44\ \mathrm{pb}^{-1}$. After the final event selection outlined below this results in a data sample of 60,000 events. A description of the H1 detector can be found in [15].

Events are selected if the scattered positron is detected in the LAr calorimeter, thus the positron must lie in the angular range $10^\circ < \theta_e < 150^\circ$ and the positron energy is required to be greater than 11 GeV. In addition to the selection of positrons the kinematic phase space is set by requiring Q^2, calculated from the positron, to be in the range $100 < Q^2 < 20\,000$ GeV^2. The inelasticity variable y calculated with the electron method (y_e) is required to be in the range $0.05 < y_e < 0.6$. In addition to minimise QED radiative effects y calculated from the JB method (y_{jb}) is required to be reconstructed close to the y_e by the additional selection that $y_{jb} - y_e > -0.15$ and $((y_{jb} - y_e)/y_{jb}) > -0.75$. The polar scattering angle for a massless parton, calculated from the positron in the QPM approximation, is required to be in the range $30^\circ < \theta_q < 150^\circ$, this ensures that the current region of the Breit frame remains in the central region of the detector where there is high acceptance and track reconstruction efficiency. The z coordinate of the event vertex is required to be within 35 cm of the nominal interaction point this together with a rejection of events that have a veto from the time-of-flight system removes beam gas associated background. The sum over all energy deposits in the calorimeters of $E - P_Z$ is required to be in the range $35 < E - P_Z < 70$ GeV, this together with the positron energy cut reduces background from misidentified photoproduction events.

Only primary vertex fitted tracks from the central jet chamber are used in this analysis which has good acceptance from 20° to 160° for transverse momenta above 120 MeV. In addition a variety of quality cuts are applied to remove badly measured tracks in a clean and well-modelled manner.

Data are corrected for detector acceptance and resolution effects using in a bin by bin manner, the resolution in a bin is smaller than the bin width. The acceptance and purities are typically above 50%.

3 DIS Scaled Momenta Spectra

In figure [1] the inclusive, event normalised, charged track scaled momentum spectrum,

$$D(x_p, Q) = (1/N_{event})\frac{dn^\pm}{dx_p}$$

where n$^\pm$ in the charged track multiplicity, is shown as a function of Q for nine different intervals of x_p. Also shown is a comparison to results from e$^+$e$^-$ annihilation events [16] where the contribution from weakly decaying short lived particles (e.g. K^0 and Λ) has been removed to be consistent with our track selection.

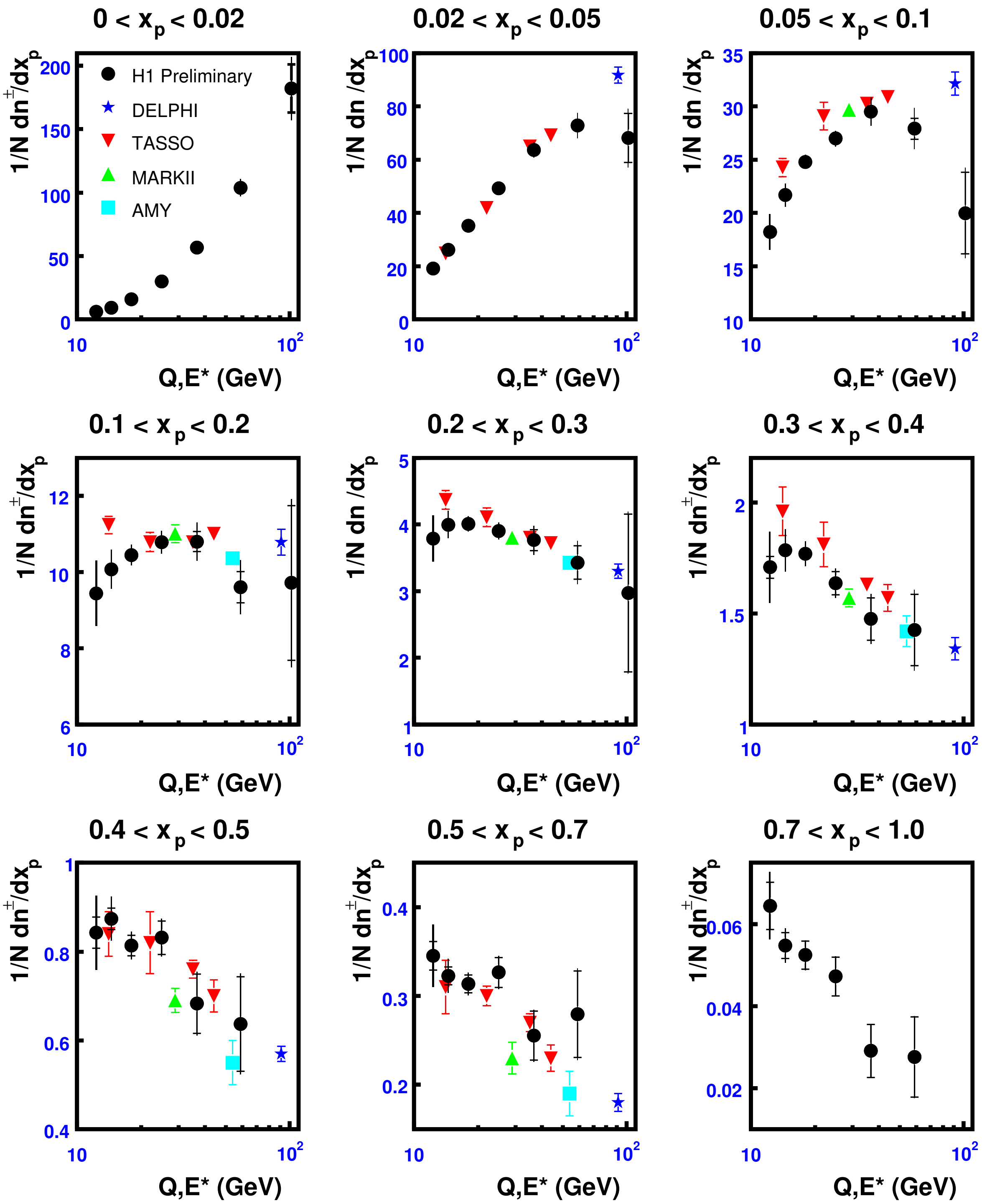

Figure 1: H1 data for the event normalised inclusive scaled momentum spectrum as a function of Q for 9 different x_p regions, The statistical error is shown by the inner error bar and full statistical and sytematic error by the full error bar, in addition there is a further scale uncertainty of 3% (5% in the lowest Q interval). Also shown are data from various e^+e^- experiments (taking $Q = E^*$). Note the suppressed zeros and large change in scale moving to higher values of x_p

Moving from low to high Q the spectra becomes softer, i.e. there is a dramatic increase in the number of hadrons with a small share of the initial parton's momentum and a decrease in those hadrons with a large share. The cause of these scaling violations (parton splitting in QCD) is the same as for the scaling violations observed for the deep inelastic structure functions.

The $\mathrm{e}^+\mathrm{e}^-$ data show the same behaviour as the ep data but with indications of a slightly softer spectrum. The agreement shown here provides a good demonstration of quark fragmentation universality.

At low Q it is expected that there should be a discrepancy between ep and $\mathrm{e}^+\mathrm{e}^-$ data. This is understood in terms of higher order QCD processes depleting the current region (as described in the introduction) at high Q a small coupling constant implies dominance of a simple QPM model. The lowest Q interval accessed in this analysis appears to show the start of this effect [17]. In the highest Q bin and at low x_p there is an unexpected and unexplained difference between the ep amd $\mathrm{e}^+\mathrm{e}^-$ results.

In order to investigate the fragmentation process in greater detail one needs to go beyond a simple comparison with $\mathrm{e}^+\mathrm{e}^-$ and compare with models that account for the known different processes present in ep scattering. In figure [2] the data is compared with Leading Order Matrix Element Monte-Carlos that then implement different models to describe higher orders and the hadronisation process.

The cluster model, as implemented in the HERWIG monte Carlo, models the hadronisation process by the formation and decay of colourless clusters. The partons are generated in a perturbative shower and at a given cut-off gluons are formed into light $q\overline{q}$ paris. Coloured objects that are close to one another are combined into colourless objects that then decay isotropically untill they can be identified with known resonances, then decay according to known branching ratios and available phase space. The RAPGAP Monte-Calro implements the Lund string model of Hadronisation and is based on the dynamics of a relativistic string (or gluonic "flux tube") stretched between coloured partons. As the partons move apart they lose kinetic energy to the string. If the string gets long enough $q\overline{q}$ pairs can be produced which are eventuly identified with mesons.

The data clearly show a preference for RAPGAP model predictions with HERWIG producing a spectrum that is too hard. At high x_p the HERWIG predictions even fail to show scaling behaviour producing a flat spectrum.

The Parton Shower model (PS), implemented in the RAPGAP Monte-Carlo, describes the fragmentation process as the splitting of a parent parton into two daughters (e.g. $q \to qg$, $q \to qq$, $g \to qq$), the splitting continues with daughters going on to form parents. The evolution of the parton shower is based on leading log Q^2 DGLAP splitting functions. Gluon coherence, which suppress emission of soft gluons at wide angles, is imposed via angular-ordering and the transverse momentum, k_t, of emitted partons is highly ordered.

It is also possible to add Soft Colour Interactions (SCI) in addition to the Parton shower. In Soft Colour Interactions soft gluons are exchanged between the partons that were produced in the parton shower and the proton remnant. Soft Colour interactions are also implemented in LEPTO [18].

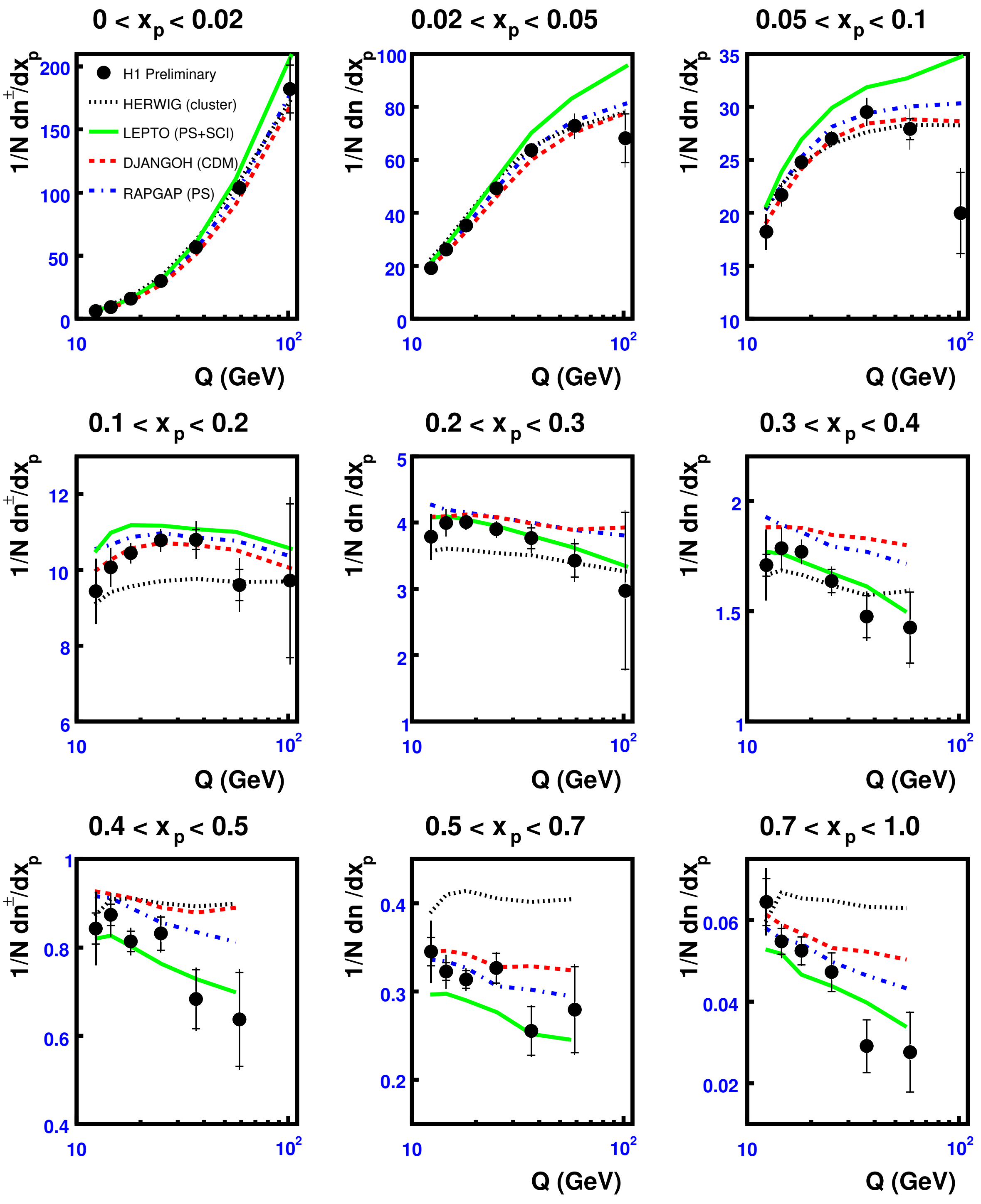

Figure 2: H1 data for the event normalised inclusive scaled momentum spectrum as a function of Q for 9 different x_p regions, The statistical error is shown by the inner error bar and full statistical and sytematic error by the full error bar, in additioan tere is a further scale uncertainty of 3% (5% in the lowest Q interval). Also shown are predictions from different models of the hadronisation process implemented in Leading order matrix element Monte-Carlo programs as described in the text and the partoncascade process

In the colour dipole model (CDM) dipoles are created between coloured partons (i.e. between quarks or quarks and the colour or anti colour of gluons) and gluon emission is treated as radiation of these dipoles. New dipoles are formed with the emitted gluons from which further radiation is possible. The radiation pattern of the dipoles, which includes interference effects, provides gluon coherence effects. The k_t of emitted partons are only weakly ordered producing a more BFKL like picture of parton splitting. ARIADNE [19] provides a implementation of the colour dipole model and is used in the DJANGO Monte Carlo program.

In general figure [2] shows that both the CDM and PS models provide a good description of the data. The CDM model provides a slightly harder description of the data but within the errors of the data neather model is favored. Both models tend to overestimate the multiplicity at higher Q but the statistical precision of the data prevents any stronger statement from being made. The SCI implementation, however, is much "softer" than the other two models and disfavoured by the data at low x_p but appears to give a better description at high x_p. This could be due to the additional gluon interactions in the SCI model which soften the spectra produced by the parton shower.

In Figure 3 the data is compared with a next-to-leading order (NLO) perturbative QCD (pQCD) calculation obtained from the Monte-Carlo program CYCLOPS [1]. In CYCLOPS the DIS cross-section is factorised into three parts; a parton-density function (PDF), the full NLO matrix element (ME), and a partonic fragmentation function (FF).

The PDF CTEQ6M [20] is taken from an available library of standard functions (the results are cross-checked using the MRST2004 PDF [22]) and the FFs are parameterisations of NLO fits to $\mathrm{e}^+\mathrm{e}^-$ data [21]. The FF used has been corrected for the mixture of light quark hadrons, charm and strangeness suppressed hadrons corresponding to the reality of H1 data. The predictions are shown for $\Lambda_{\overline{MS}}^{(5)} = 266\mathrm{MeV}$.

In order for the FF picture to be a valid description, the hadrons should be produced in close rapidity to the parent parton. The author of the CYCLOPS program suggests [1] using an infrared safe area $y_h > y_{min}$ where y_h is the rapidity of the hadron in the Breit frame and $y_{min} \approx 1$. This requirement may be recast in terms of a Q dependent lower bound on x_p of

$$x_P^{safe} = \frac{2m_T}{Q} \times \frac{1}{\sqrt{(}1 - (\tanh\ y_{min})^2)} \tag{1}$$

With a transverse mass, m_T, of $\sim 0.5\mathrm{GeV}$ this gives a safe limit of $x_pQ > 1.5\mathrm{GeV}$ for this analysis this essentially corresponds to $x_p > 0.1$, in addition the parameterisation of the fragmentation functions are done for $x_p > 0.1$. As a result the data is only compared to NLO QCD theory for $x_p > 0.1$.

In Figure 3 it can clearly be seen that the uncertainties associated with the change in scale or PDF are small and much smaller than the differences between different fragmentation function parameterisations. The data is clearly sensitive to the different fragmentation function parameterisations with the kkp fit providing a very good description of the data for $x_p > 0.2$. Both the akk and pkh fits fail to describe the data and all predictions fail to describe the data in the lowest x_p interval.

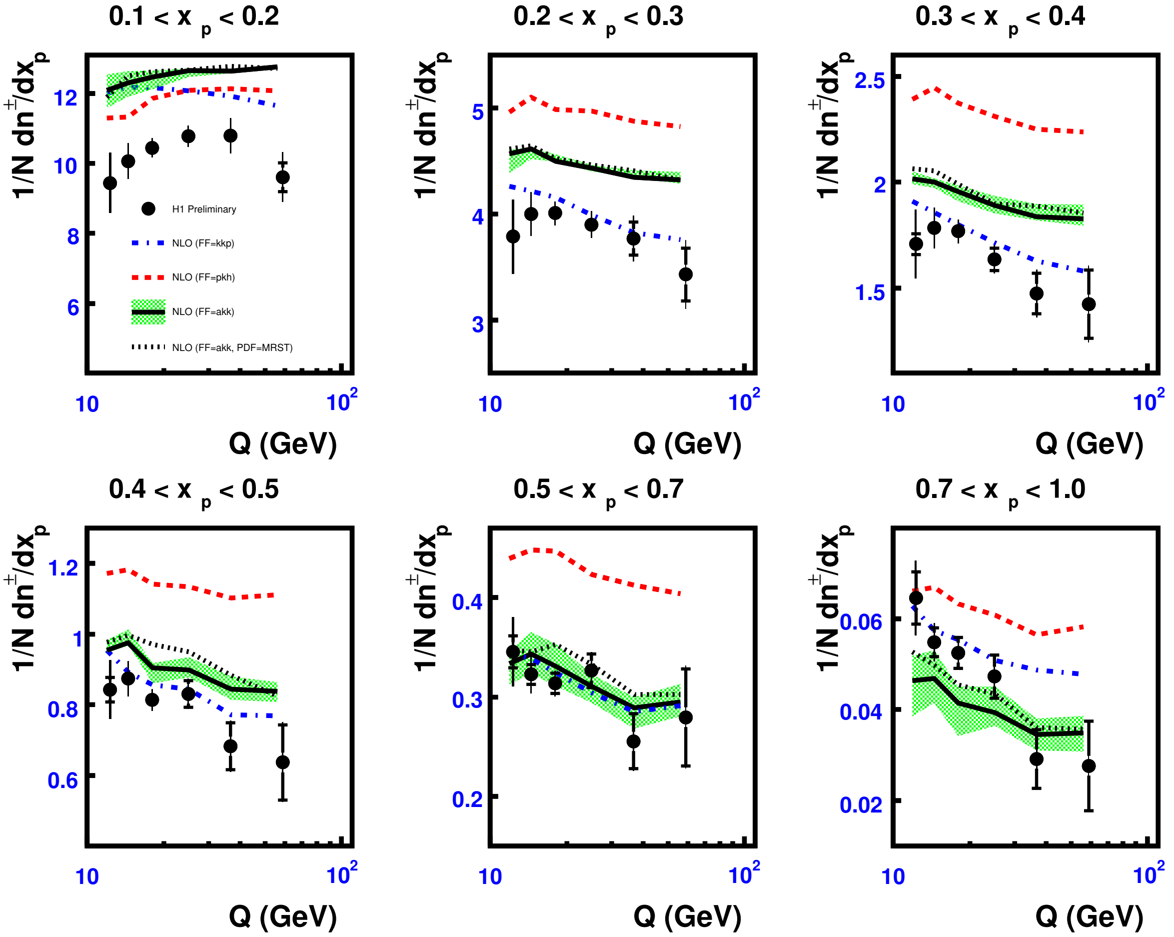

Figure 3: H1 data for the event normalised inclusive scaled momentum spectrum as a function of Q for 6 different x_p regions. Also shown are NLO QCD CYCLOPS predictions for three different fragmentation functions kkp (dot-dashed line), akk (solid), and pkh (dashed). The scale uncertainty for the akk predictions are also shown as a shaded band. As standard the CTEQ6.1 PDF is used, the effect of using the MRST2004 PDF for the akk predictions is also shown (dotted).

4 Conclusions

The cross-section normalised scaled momentum distribution (x_p) of charged final state hadrons has been measured in DIS ep collisions by H1 at High Q^2 in the Breit frame of reference and compared with a variety of different models.

The results support the concept of quark fragmentation universality in ep collisions and $\mathrm{e^+e^-}$ annihilation.

The Monte Carlo which model the parton cascade by implementing either the colour dipole model or parton showers describe the data. The string model of hadronisation provides a better description of the data than the cluster model as implemented in HERWIG.

The data show a clear sesitivity to the fragmentation fuction used in the NLO QCD predictions while other contributions the the theoritical error (scale and PDF) are small.

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