Tests of QCD with Particle Production at HERA: Review and Outlook.

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Precision measurements of the ep hadronic final state made by the H1 and ZEUS collaborations at HERA are used to test exact perturbative QCD calculations and non-perturbative QCD schemes in a variety of different experimental environments.

1 Introduction

Since 1992 the HERA experiments H1 and ZEUS have been assembling a body of precise measurements of ep induced hadronic final states. Their usefulness in quantifying the success of the theory of strong interactions (QCD) and probing proton and photon structure cannot be overstated. Owing to the large kinematic range in Bjorken-x and the virtuality of the exchanged boson, Q^2, ($10^{-5} \lesssim x \lesssim 0.5$ and $0 \lesssim Q^2 \lesssim 50000$ GeV^2, respectively) opened up by HERA it is possible to select regions of phase space which are associated with different parton configurations and make precision measurements of hadron production there. Deeply inelastic ep scattering (DIS) at low values of Bjorken-x ($x \sim 10^{-4}$) permits a well-developed parton cascade to occur before the interaction with the exchanged boson and the form of this evolution is still one of the open questions in pQCD today. Conversely, for high values of Q^2 the available phase space permits a time-like evolution from a parton after the interaction with the exchanged boson in a manner analogous to QCD evolution following e^+e^- annihilation. This allows the study of the universality of hadron production and (for large values of Bjorken-x) precisely tests pQCD in an environment devoid of large theoretical uncertainties associated with the space-like evolution of partons from the proton. Hadronic final state studies also allow the possiblity to discriminate between the non-pQCD models of hadronisation and, in particular, to study the influence of an extended baryon remnant system on this process.

This paper reviews current open questions in the ep hadronic final state and discusses tests of pQCD and non-pQCD schemes made with measurements of particle spectra. Results on jet physics are covered elsewhere [1]

2 Forward π^0 Production

The presence of particles with large values of transverse momentum (p_T) is indicative of a hard partonic sub-process and thus can be used to directly test pQCD calculations [2]. It was therefore suggested [3] that measurements of the forward π^0 cross-section could help to resolve one of the open questions at HERA: how do partons evolve from the proton ? Parton evolution based on the DGLAP [4] equations successfully describes all inclusive measurements of the proton structure function F_2. However, this scheme sums terms in $ln(Q^2)$ and ignores terms in $ln(1/x)$ which should play a significant role in the low Bjorken-x domain opened by HERA and therefore BFKL [5] evolution which, conversely, sums terms in $ln(1/x)$ is expected to become applicable. Although measurements of F_2 offer no discrimination between the two schemes, the different dynamical features of the two approaches suggests that the hadronic final state may offer a means of observing BFKL effects. DGLAP evolution imposes a strong increasing ordering on k_T, the transverse momentum of the emitted parton and a weak decreasing ordering in the fractional momentum x of the propagating parton as the parton "ladder" develops away from the proton. However, BFKL evolution imposes a strong ordering in x and no ordering in k_T, allowing partons to take a "random walk" in k_T and thus would give rise to more high momentum parton emissions than from DGLAP evolution.

It would then be expected that measurements of particle production in the region associated with this parton ladder would be sensitive to evolution effects. In fact, a series of hadronic final state measurements on transverse energy flow and jet and particle production in the forward (ie close to the proton) direction have already been made [6,7]. A recent highlight of these works is the measurement of high p_T π^0 mesons [7]. In this study π^0 mesons with values of transverse momentum in the photon-proton hadronic centre of mass system of $p_T > 2.5$ GeV were selected. Values of the polar angle, θ, measured with respect to the incoming proton direction in the HERA laboratory system were restricted to $5^0 < \theta < 25^0$ and the laboratory system π^0 energy scaled by the incoming proton energy ($x_\pi = E_\pi/E_{proton}$) was required to be greater than 0.01. The kinematic range in Q^2 and the inelasticity variable, y, was restricted to $2 < Q^2 < 70$ GeV^2 and $0.1 < y < 0.6$.

Figure 2 shows the forward π^0 cross-section (left) and DIS event-normalised rate (right) as a function of Bjorken-x for three different intervals of Q^2. The cross-section rises towards low Bjorken-x for each of the Q^2 ranges although the rate is flat. Calculations based on leading order BFKL dynamics [8] describe the data best although they fail to match the measured cross-section at the lowest values of Bjorken-x and Q^2. Calculations based on DGLAP evolution

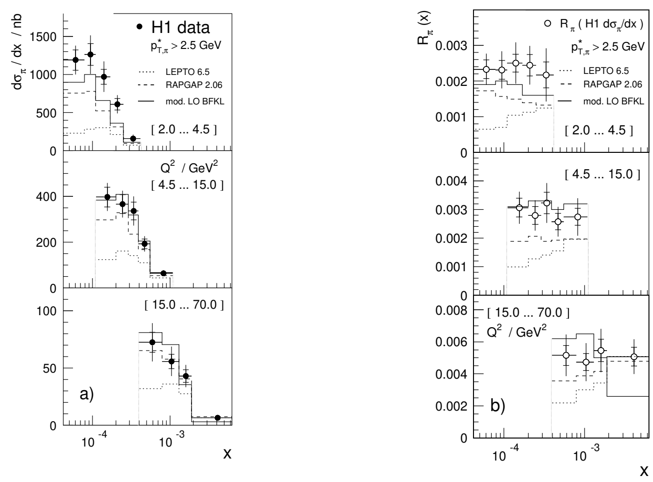

Figure 1: The forward π^0 cross-section (left) and DIS event normalised-rate (right) as a function of Bjorken-x for different intervals of Q^2.

from the proton alone (LEPTO [9]) fail to describe the data. Partonic structure can also be assigned to the resolved photon thus allowing DGLAP evolution from the photon and the proton. Calculations based on this picture are also shown (RAPGAP [10]) and they come close to the data although, like the BFKL calculations, these fail at the lowest measured values of Bjorken-x and Q^2.

It is the author's opinion that the next step for these analyses must be the exploitation of the full ep event information. One such proposed analysis is using multi-particle correlations which are directly sensitive to the presence or absence of strong k_T ordering in parton emissions [11]. The H1 and ZEUS experiments are strongly encouraged to pursue this.

3 Inclusive Particle Production in the Breit Frame

In addition to measuring the rate of high momentum particles, the momentum spectra of produced particles is also instructive in testing pQCD. The modified leading log approximation (MLLA) under the assumptions of local parton hadron duality (LPHD) has proven successful in e^+e^- experiments at describing the centre-of-mass energy dependence of the peak position and width of particle fragmentation functions. For ep collisions at HERA, the current region of the Breit frame is the appropriate region of phase space to compare particle production in DIS with that in e^+e^-. The Breit frame is aligned with the photon-proton centre of mass frame but boosted along a common z direction such that the incident photon has zero energy, zero transverse momentum and a z component of momentum -Q. The negative z-axis is chosen to be in the direction of the incoming photon and is referred to as the current hemisphere of the interaction and is the region of phase space that can be associated with the fragmentation of the struck quark in the quark parton model. The DIS hadronic final state in the current region of the Breit frame can therefore be compared to that produced in a single hemisphere of an e^+e^- collision if the centre of mass energy is equal to Q.

Figure 2 (left) shows the evolution of the peak position, width, skewness and kurtosis of the fragmentation function $\xi = ln(\frac{1}{x_p})$ with Q for charged particles inclusively produced in the current region of the Breit frame, in which x_p is the particle momentum in the Breit frame scaled with Q. Results from e^+e^- experiments are shown and agree well with the DIS results from ZEUS[12] for values of $Q^2 \gtrsim 100$ GeV^2, supporting the hypothesis of the universality of parton fragmentation in this region.

A comparison is also with MLLA predictions of Dokshitzer et al.[13] with different values of the cascade cut-off, Q_0 ($Q_0 = \Lambda$:full line, $Q_0 = 2\Lambda$: dashed line, $Q_0 = 3\Lambda$: dotted line) and the limiting spectrum predictions of Fong and Webber:dashed-dotted line[14]. A consistent description of the mean, width, skewness and kurtosis cannot be achieved. One possible explanation for this could be the massless assumptions made in the MLLA[15].

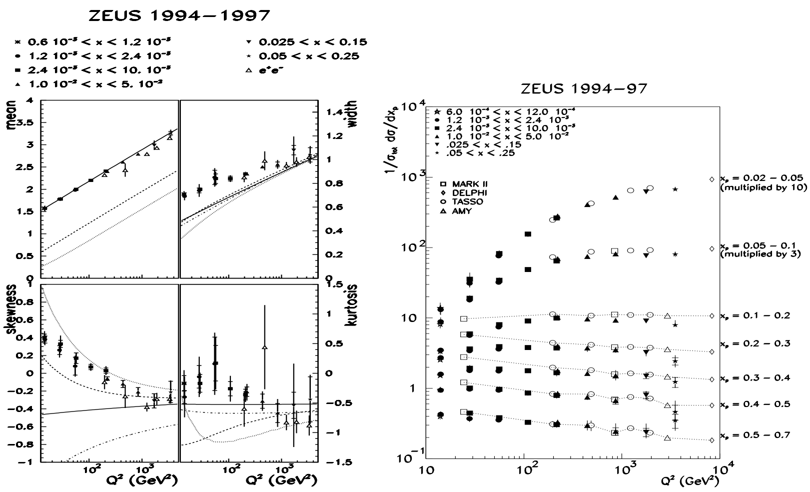

Figure 2: The evolution of the higher moments of the fragmentation function ξ (left) and x_p (right) for inclusively produced charged particles in the current region of the Breit frame as a function of Q. Results from e^+e^- collisions and pQCD-based calculations are also shown.

Another way to study the evolution of particle fragmentation functions with Q is via their "scaling violations". Figure 2 (right) shows the dependence of $\frac{1}{\sigma_{tot}}\frac{d\sigma}{dx_p}$ on x_p and Q as measured by the ZEUS collaboration. Again e^+e^- results are also shown and, with the scale as their centre of mass energies, agree well with the DIS data for $Q^2 \gtrsim 100$ GeV^2. For $Q^2 \lesssim 100$ GeV^2 pQCD processes in DIS such as boson-gluon fusion and QCD-Compton which are absent in e^+e^- produce a lower multiplicity in the current region of the Breit frame [12,16] than in a single e^+e^- hemisphere.

The qualitative features of these distributions can be understood as a softening of the particle spectra with increasing Q owing to an increased phase space for QCD emissions. For large values of x_p and Q precise calculations to next-to-leading order (NLO) QCD which are convoluted with charged particle fragmentation functions derived from e^+e^- results can be used to make a direct comparison with the data and these are also shown. They describe the data reasonably well at the higher values of Q^2 ($Q^2 \gtrsim 100$ GeV^2) at which the factorisation scale dependence effects are minimised. Ultimately, such studies can be used to provide a measurement of α_s, complementary to derivations from (2+1) jet rates. However, owing to current theoretical uncertainties, namely the factorisation scale dependence and parton density assumptions, it is unclear if such a measurement will ever be competitive [17]. More current results on fragmentation studies at HERA can be found in [12] and [16].

With regard to future directions, it is the author's view that simply making more statistically precise studies of existing measurements will not help the study of the environmental independence of fragmentation. Instead, works such as [18] should be considered which suggests comparing DIS and e^+e^- results after applying a series of cuts to suppress the QCD effects from proton structure which are present in the current region of the Breit frame. Furthermore, one of the next steps in charged particle multiplicity-based pQCD tests should be to expand those studies which use the full event information such as [19].

4 Baryon Number Propagation

In addition to precision tests of pQCD, HERA is also in a position to make a useful contribution in studying non-pQCD processes and discriminating between the plethora of available schemes. One such recent study is that of baryon number propagation and this produced one of the most remarkable results on the hadronic final state to come from HERA so far [20]. A positive baryon number is seen in the backward region of the H1 detector, up to eight units of rapidity away from the leading baryon regime. The $p\bar{p}$ asymmetry $2 \cdot \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}$, formed from the $p(\bar{p})$ yield $N_p(N_{\bar{p}})$, is studied in the photon hemisphere in photoproduction interactions. Owing to experimental particle identification constraints, the $p\bar{p}$ are restricted to a range in pseudorapidity and p_T, as measured in the HERA laboratory frame, of ($|\eta| < 1$ and $0.3 < p_T < 0.6$ GeV). The H1 preliminary measurement of the asymmetry is shown in figure 4 as a function of the inclusive charged particle multiplicity in the same angular region as the $p\bar{p}$. A significant, positive baryon asymmetry is seen which rises with multiplicity. Calculations from [21] in which the baryon number is assumed to be propagated via a gluon (quark) exchange mechanism are also shown as a solid (dashed) line. The gluonic mechanism describes the data well. The PHOJET [22] model of photoproduction interactions which uses Lund string fragmentation [23] and treats baryon number assignment via the conventional diquark+quark approach predicts no asymmetry in this region.

It is now vital that the H1 experiment publishes this analysis as a final result and that this observation is also verified by the ZEUS collaboration. Studies of strange hyperons should also be performed as they may give rise to an enhanced baryon asymmetry owing to the suppression of strange-flavoured baryons in the fragmentation process.

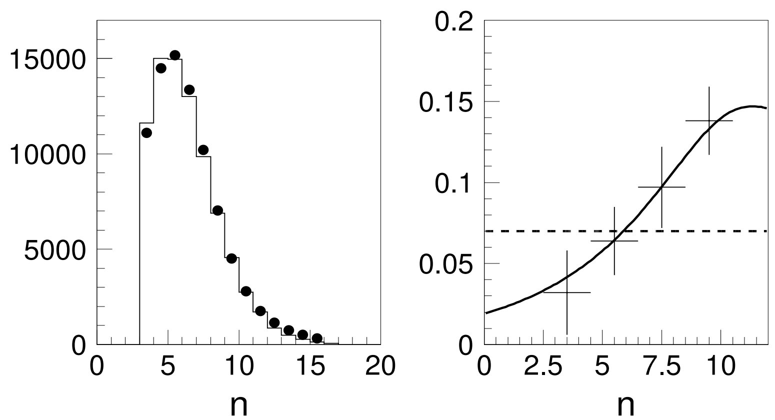

Figure 3: H1 preliminary measurements of the charged particle multiplicity (N) in the region $|\eta| < 1$ (left) and the $p\bar{p}$ asymmetry, $2 \cdot \frac{N_p - N_{\bar{p}}}{N_p + N_{\bar{p}}}$ as a function of N. Calculations assuming a gluon (quark) exchange mechanism for baryon number propagation are also shown as solid (dashed) lines.

5 Summary

A review of results on particle production from ep collisions at HERA has been presented. This work has enabled precise tests of pQCD and non-pQCD calculations to be made.

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