H1 Note 11/95 - 460

Hadronic Final States in Deep Inelastic Scattering *

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Abstract

Recent studies of the hadronic final state in deep inelastic ep scattering at HERA are reviewed. The contribution that can be made to the measurement of QCD effects by looking at exclusive final states is highlighted, as well as the understanding of the interplay with soft, non-perturbative processes.

1. Introduction

It is becoming increasingly clear that a measurement of *e.g.* the proton structure function F_2 is essentially an inclusive cross-section measurement and as such can be very insensitive to significant effects in small areas of phase space. As well as conducting a general review of recent analyses of hadronic final states, it is the object of this review to draw attention to such areas and to assess their value for future studies.

The review will confine itself to experiments carried out at the HERA accelerator at DESY by the H1 and ZEUS collaborations on data taken in 1993 and in 1994. This therefore implies throughout an incident positron of momentum 26.7 GeV/c interacting with a 820 GeV/c proton. Typically each experiment obtained some 400 nb^{-1} of data in 1993 and 4 pb^{-1} in 1994 although the analyses mentioned here will be based on somewhat smaller subsamples. The reader is directed to the references for the details of data selection in each case but it is relevant to remark that all analyses have kinematic ranges limited by a cut at high y, or equivalently high W^2, in order that the positron energy be high enough ($\approx$ 10 GeV) to make sure that identification is clean and there is negligible background from the huge cross-section of photoproduction events and by a cut at low y, or low W^2 caused, essentially, by the beam pipe aperture. The same cuts limit the two extremes of QED radiation. The net result is that data is restricted to a comparatively narrow diagonal band on the usual $\ln Q^2$ vs. $\ln x_{Bj}$ plot with a significant gap between collider data and

*Talk at 3rd UK Phenomenology Initiative: Proton, Photon and Pomeron Structure, Durham, September, 1995 fixed target data which is typically at comparable but slightly smaller Q^2 and larger x_{Bj}. The restriction also results in a W^2 range which is at least a factor two smaller than the available Q^2 range, a significant fact when trying to establish correct energy scales for various processes.

2. Fragmentation

At the level of the naïve quark-parton model the entire hadronic state may be viewed as the fragmented product of a scattered quark and the proton remnant. Earlier analyses [1,2] conducted in the Breit frame of reference [3] showed that the charged hadron fragmentation spectrum not only had the same shape as that seen in a single hemisphere of an e^+e^- event but also that the shape evolved in Q in exactly the same way as the latter does in terms of the e^+e^- centre of mass energy, E^*. Even further, the absolute normalization, the average charged multiplicity, showed very good agreement except at low Q, or E^*, where there was a significant shortfall.

A new H1 analysis of multiplicity distributions [4] in the current hemisphere of the hadronic CMS frame shows good agreement of the charged hadronic multiplicity with earlier DIS experiments as a function of W (see Fig.1a) and establishes the need for a non-linear behaviour in $\ln W$ as is the case with $\ln E^*$ in e^+e^- . A direct comparison with e^+e^- multiplicities with, now, W equated with E^* again shows a small but systematic shortfall. The agreement of either measure with e^+e^- multiplicities is an important statement about quark universality, but the approximate *simultaneous* agreement of both Breit frame multiplicities as a function of Q and hadronic CMS multiplicities as a function of W is a consequence of Feynman scaling [5] and it is now incumbent on us all to ensure that we are genuinely comparing like with like and that there is *e.g.* no contamination from the target end of the fragmentation which could well be different because of its diquark nature. Further Breit frame analysis at this workshop [6] has now shown that the remaining e^+e^- multiplicity discrepancy can be successfully attributed to contributions from higher order diagrams (boson-gluon fusion and initial state QCD bremsstrahlung) that do not have an equivalent in e^+e^- interactions.

The new analysis shows (Fig.1b) that the multiplicity normalised by its dispersion is almost the expected constant expected from KNO scaling [9] but is already well above the $\sqrt{3}$ asymptotic value predicted by double leading logarithm approximation to QCD, and is still rising slowly.

The ZEUS experiment has also displayed spectra in the hadronic CMS [7] and find, as in H1 data [8], that the shortfall of the average multiplicity in ep data compared to e^+e^- data at similar $W = E^*$ is concentrated at low Feynman x_F. This again raises the suspicion that the discrepancy may be explicable in terms of target activity. The ZEUS analysis compares the rise in average particle transverse momentum squared, p_t^{*2} as a function of x_F (the 'seagull' plot, Fig.2) for DIS data at HERA and fixed target energies. The rise is due to the increased probability of the particle being associated with a high transverse momentum parton, *i.e.* QCD effects. Although these data are at similar Q^2 the HERA data is at *very* low x_{Bj}. The particle-parton correlation thus occurs at considerably lower particle x_F and so the much higher average p_t^{*2} observed does little to contribute to the choice of W or Q as better QCD scales.

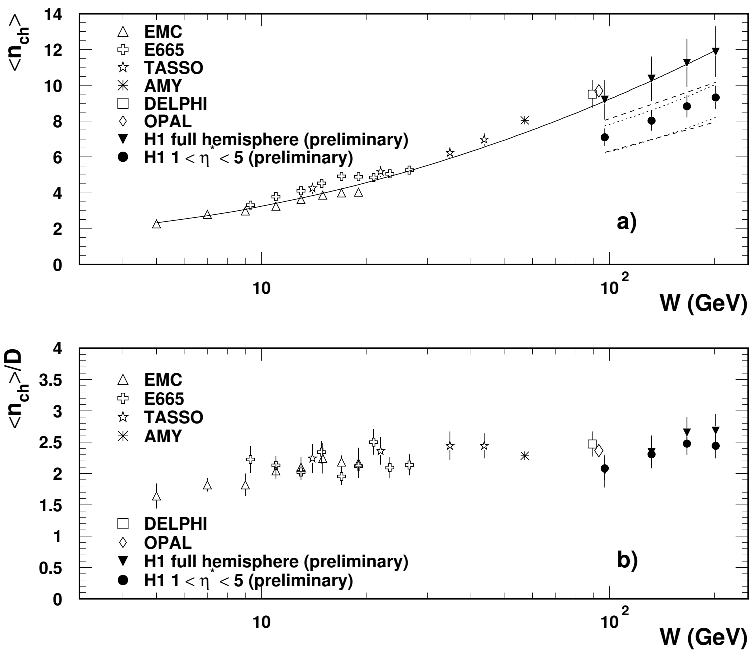

Figure 1: *Preliminary H1 data showing (a) average charged hadronic multiplicity in the current region of the hadronic CMS system as a function of* W *compared to fixed target DIS results and selected* e^+e^- *data as a function of* E^**, and (b) the same variable normalized to its dispersion.*

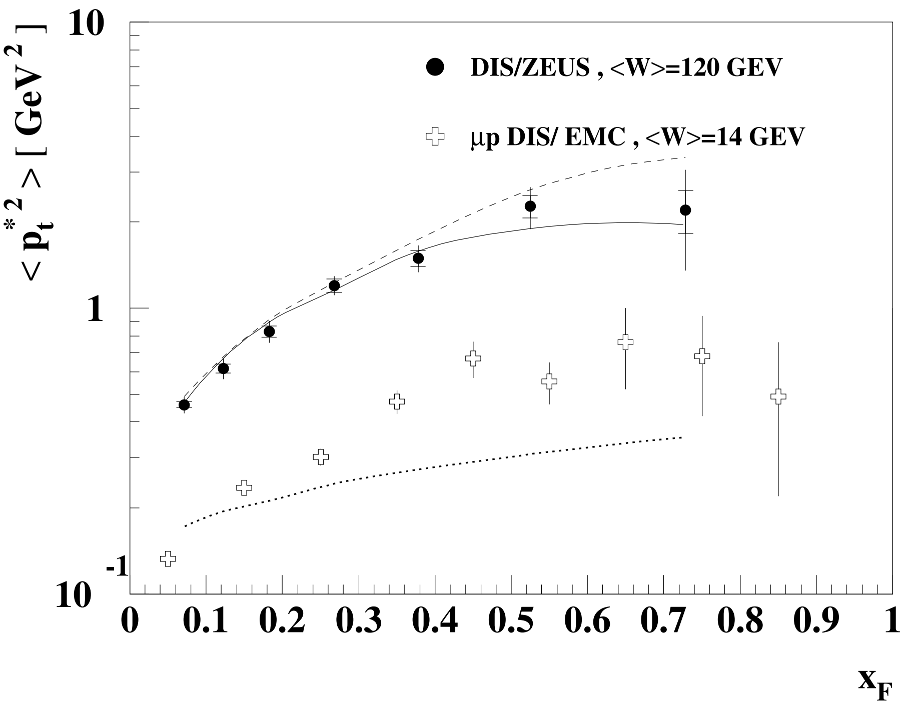

Figure 2: *Average charged particle transverse momentum squared as a function of Feynman* x_F *compared to fixed target DIS data at a similar* Q^2 *but very different* W*. The dotted line is the expectation from a simple quark-parton model with hadronisation and shows the need for QCD effects.*

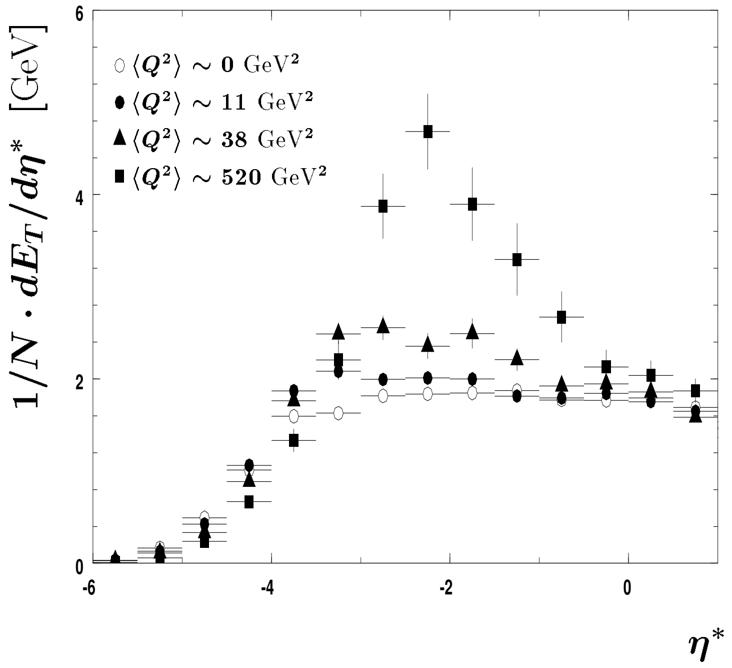

Figure 3: *The transverse energy density as a function of hadronic CMS pseudorapidity at various Q^2 values from photoproduction to DIS.*

The priorities of both major experiments have so far implied that the fragmentation studies which have been made still make no serious attempt at particle identification. Nevertheless analyses are now available [10,11] on the spectra of neutral strange particles from the reconstruction of secondary decay vertices. These indicate that there is *e.g.* about 1/4 K^0 produced in DIS events in this energy range. There is some evidence for a strangeness suppression factor $P_s/P_u \sim 0.2$ in fragmentation, slightly lower than in most e^+e^- fragmentation analyses, with ZEUS preferring an even lower value for Λ^0s. There appears to be no difference in the ratio of K^0s to average charged multiplicity in identified diffractive interactions which might have been expected in a scenario of more flavour democracy.

3. The transition from photoproduction to DIS

An interesting observation on the nature of this workshop is the difficulty of maintaining *separate* group activities. This may be illustrated readily by reporting on an analysis [12] which combines photoproduction data with DIS data from a huge range of Q^2 to show, (Fig.3), the growth of the transverse energy peak in the current hemisphere of the hadronic CMS, as the exchanged photon becomes increasingly virtual. This virtuality of the photon dies extremely quickly with rapidity, however, and the ~ 2 GeV per unit of rapidity in the central region has almost no Q^2 dependence whatsoever.

There are two major Monte Carlo simulations popular for hadronic final state analyses at the moment. They are the technique of matching first order matrix elements with parton showers (MEPS) and the colour dipole radiation model (CDM), supplemented by the insertion of hard initial state gluons via the boson gluon fusion diagram (BGF). Their relative performances are excellently summarised in Fig.4 where the transverse energy density in two distinct pseudorapidity intervals is traced over three orders of magnitude in Q^2. It appears that MEPS is able to describe the rise in the current region but falls far too low

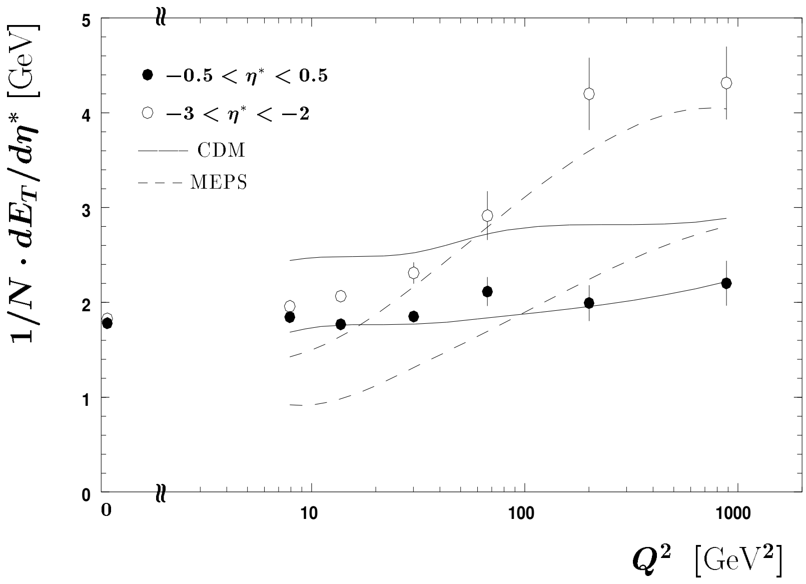

Figure 4: *The Q^2 dependence of the transverse energy density in the peak of the photon fragmentation region and in the hadronic plateau region with the predictions of two major Monte Carlo models.*

at low Q^2 and cannot get the Q^2 independence of energy density in the hadronic plateau region. The performance of CDMBGF is almost orthogonal in both respects.

Although Q^2 independent, the height of the plateau does depend (logarithmically) on the W scale and it is encouraging for theories of universality and factorization that the observed level fits neatly with the results of hadron-hadron interactions bridging the kinematic gap between ISR and S$p\bar{p}$S experiments.

A most important area of the transition from photoproduction to DIS is that of looking at the exclusive channel of ρ production where vector meson dominance implies elastic, and *thus* diffractive, scattering. The latest analyses [14,13] have confirmed that there is, however, a big difference between on-shell and off-shell diffractive scattering of vector mesons. Whereas the former is pure s-channel helicity conserving, the latter soon flips into being dominated by production through longitudinally polarised virtual photons. Although it is by no means yet certain, the present indications are that simultaneously the slope of the momentum transfer, t, to the proton goes from values ≈ 10 (GeV)$^{-2}$ to ~half that value. The ep collider experiments establish the gentle rise of cross-section in the $Q^2 = 0$ elastic channel as seen as almost a trade-mark of diffractive scattering. As may be seen from Fig.5, however, the indication is that for DIS exclusive ρ production, as with inclusive scattering, the energy dependence is much steeper as would be expected from the hard Lipatov pomeron. Further possible evidence for related mechanisms is reviewed in the next section.

4. Alternative pQCD expansions

The ability of final state analyses to concentrate on a small area of phase space will undoubtedly be useful in the continuing debate as to whether the advantages of the BFKL

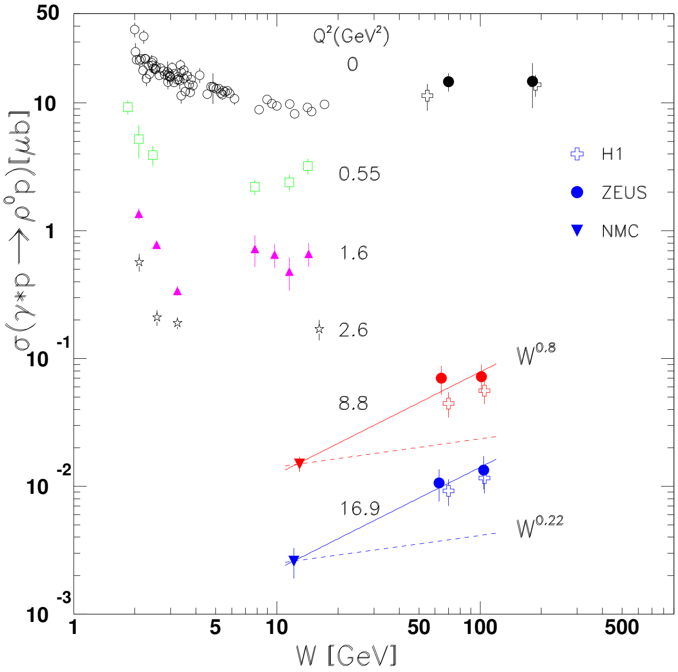

Figure 5: *The dependence of the total cross-section for exclusive ρ production as a function of centre of mass energy W for photoproduction and DIS at several values of photon virtuality, Q^2. The lines of slope $W^{0.8}$ and $W^{0.22}$ are to guide the eye.*

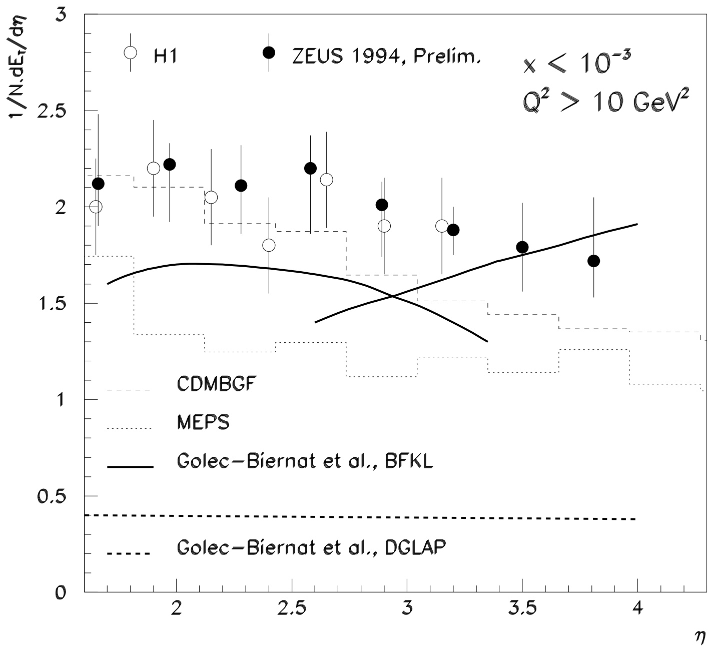

Figure 6: *Average transverse energy per unit of rapidity with the predictions from two full Monte Carlo simulations (CDMBGF,MEPS) and two parton-level calculations (BFKL,DGLAP) with no hadronisation. See text for more details of predictions.*

$x_{BJ} \times 10^3$	Observed Events	MEPS	CDM	σ_{jet} (pb)
$0.2 \to 1.0$	271	141	282	$709 \pm 42 \pm 166$
$1.0 \to 2.0$	158	101	108	$475 \pm 39 \pm 110$

Table 1: *Number of events in data, and predictions, with a found forward jet as specified in the text, together with the inclusive cross-section.*

perturbative expansion of QCD in terms of $\ln 1/x$ over the 'standard' DGLAP $\ln Q^2$ expansion can yet be seen. So far [15] the technique was to look at the transverse energy, E_t, flow for very low x events in the forward direction. As may be seen in Fig.6, both of the major Monte Carlo models discussed in the last section underestimate the constancy of the ~ 2 GeV per unit of rapidity seen in the data although CDMBGF is closer in magnitude. The MEPS model owes much to the DGLAP approximations whereas the colour dipole has no concept of k_t ordering and is thus more akin to BFKL philosophy. The only full BFKL predictions which have been made so far are analytic calculations and should have some E_t flow added to them to allow for hadronisation effects.

An alternative [16] method is to look for gluon jets having a large share of the proton's momentum, $x_{jet} > 0.025$, in the forward direction whilst simultaneously limiting severely the phase space available for DGLAP evolution by requiring that these jets have a $p_\perp^2$ commensurate with Q^2 (in practice $0.5 < p_\perp^2/Q^2 < 4$) whilst giving every opportunity for a BFKL ladder diagram by demanding x_{Bj} to be small. Table 1 displays the number and inclusive cross-section for events containing such jets in a 330 pb^{-1} sample in two different x_{Bj} regions compared to predictions from the two major Monte Carlos. Again the conclusion is that CDMBGF does better. The ratio of inclusive cross-sections gives 1.49 ± 0.25 to be compared to analytic calculations of 1.69 for a full BFKL ladder diagram and 1.03 when the gluon rungs are omitted. The field is developing rapidly but it is clear that a full simulation program is needed based on BFKL. It is encouraging to see this beginning at this workshop [17].

5. Measurements of α_s

The Compton QCD and BGF Feynman diagrams are first order ($\alpha_e\alpha_s$) QCD processes the cross-section for which may be used to measure α_s and its dependence on Q^2. To fix the renormalization gauge the contributions to these processes from second order diagrams must be known and this is now the case via the programs DISJET and PROJET at the level of partons resolved by the JADE jet-finding algorithm. The procedure is thus to use this algorithm on the total hadronic state and to find the number of jets as a function of the dimensionless jet resolution parameter, $y_c = 2E_iE_j(1 - \cos\theta_{ij})/W^2$. Unfortunately, jet-finding in the forward direction to the required precision is unreliable with this algorithm and the data must be further restricted either by demanding that two jets be found within a certain angular range ($10^o < \theta_{jet} < 145^o$) or that both jets have a significant share ($\geq$10%) of the total dijet energy-momentum. Dijet to total cross-sections ratios with a given ($y_c = 0.02$) resolution, chosen to minimise sensitivity, are converted to equivalent partonic values using the standard, first order, Monte Carlo programs and at this stage a further complication arises in that it is found that $Q^2 > 100$ GeV^2 events must be selected

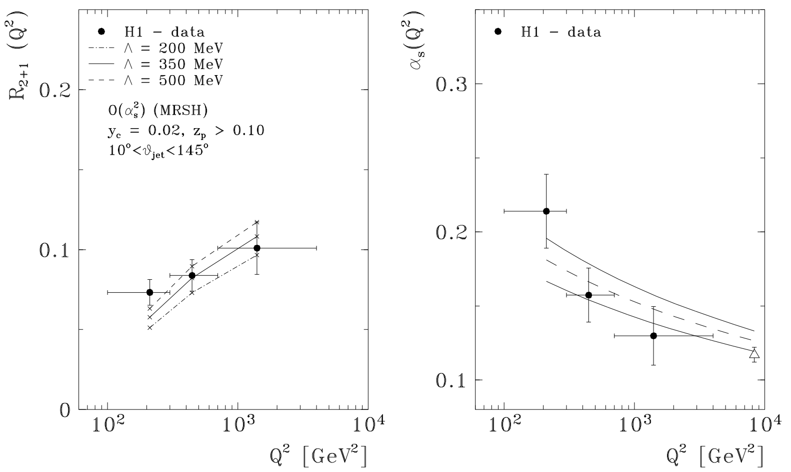

Figure 7: *Preliminary H1 data showing the ratio of the number of events having the '2+1' topology (i.e. two high E_t jets in addition to the beam remnant) to both '2+1' and '1+1' events when the jets are corrected back to the parton level, and resultant values of α_s in the same Q^2 intervals.*

in order that Monte Carlo sensitivity to hadronisation effects is small enough.

Calculated in this way, partonic cross-sections *increase* with Q^2 as may be seen in Fig.7. It is the task of the second-order Monte Carlo programs to predict the increase of phase space to fit this rise to a fall in α_s as is also shown in Fig.7. In principle the majority of this phase space effect should be dealt with by the $1/W^2$ term in the definition of y_c. If the term were to be replaced by $1/Q^2$, the greater dynamic range would indeed produce this effect and there would be a better integration with the dependent variable of $\alpha_s(Q^2)$. The higher order Monte Carlos would have to be modified to allow this and, as yet, it is the μ^2/Q^2 scale uncertainty which is still the greatest source of error. The results of the H1 [18] and ZEUS [19] experiments are shown together in Fig.8 with a combined extrapolation to $\alpha_s(\mathrm{M}_Z) = 0.120 \pm 0.005 \pm 0.007$ compatible with, and soon, possibly, to have a competitive error with, the world average of 0.117 ± 0.005.

6. Determination of the gluon density

The above method of analysis may be effectively reversed by assuming that $\alpha_s(Q^2)$ is well known and working in the kinematic area where the quark density functions are measured by fixed target experiments. The unknown distribution function for gluons may then be fitted to the observed cross-section of dijet events as a function of x. The results of a leading order analysis [20] of this method of directly observing the gluon density in the proton are shown in Fig.9 where they are compared to methods involving the gradient of the F_2, QCD fits and use of the J/Ψ channel, as well as to current structure function assumptions.

7. Conclusions

Apart from a few small and understandable exceptions, it appears that the comparison of ep and e^+e^- interactions suggests that the fragmentation of partons is a universal phenomenon. As virtuality increases, increasing energy is deposited in the current region but the hadron plateau is dependent only on the overall energy scale. Diffractive phenomena

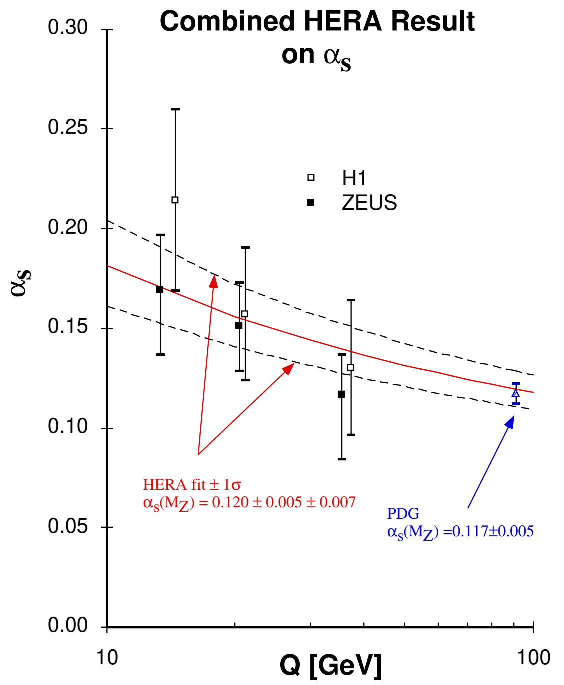

Figure 8: *Combined H1 and ZEUS fit for $\alpha_s(Q)$ with the one standard deviation error curve and the accepted particle data group world average.*

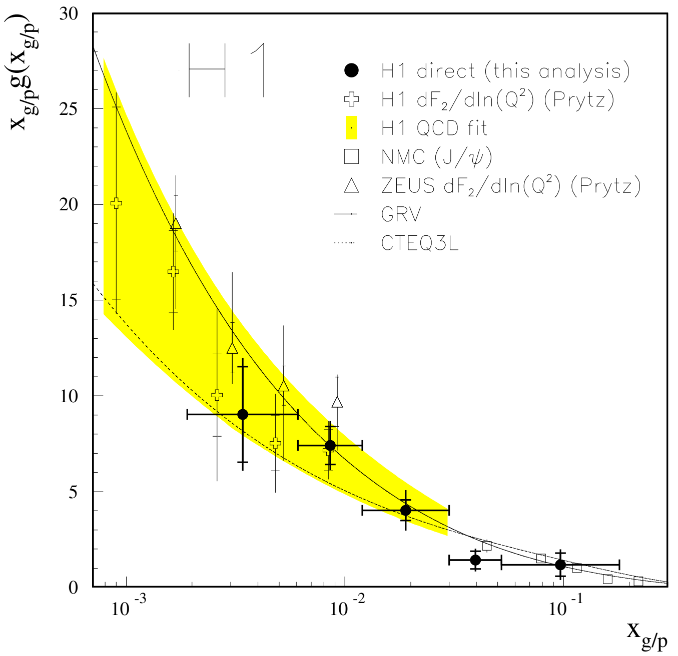

Figure 9: *Combined HERA data on gluon density in the proton emphasizing the H1 analysis (solid circles) which counts the number of dijet events.*

become much ‘harder’, and there is some evidence in the forward direction for the need for a $\ln 1/x$ pQCD expansion. If structure functions are presumed known, α_s may be derived from dijet event cross-sections and vice versa is also true for the derivation of the gluon density in the proton.

Acknowledgements

The author would like to thank the organisers of the Durham meeting for an enjoyable and productive week, and wishes to acknowledge the hard work of all of his colleagues on both experiments who have allowed access to the results of their analyses. Space has enforced rather inadequate coverage of details, and in some cases total exclusion. I apologise. Comments made within this review are the opinions only of the author in a personal capacity and errors of interpretation should also be so attributed.

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