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CONFERENCE SUMMARY: QUANTUM CHROMODYNAMICS AT SMALL x *

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The range of electroproduction kinematics $x_{Bj} = Q^2/(2p \cdot q) \geq 10^{-4}$ at $Q^2 \geq 10\ GeV^2$ accessible at the HERA $e-p$ collider will provide a challenging high energy testing ground for quantum chromodynamics in a regime where the gluon distribution of the proton is expected to saturate and new types of multi-scattering higher twist contributions to structure functions become important. In this summary I give a brief overview of the recent theoretical work presented at the Hamburg conference.

INTRODUCTION

The remarkable extension of electroproduction kinematics made possible by the $e-p$ collider HERA will allow the first detailed studies of QCD at values of x_{Bj} as small as 10^{-4}, one hundred times smaller than present experiments. To leading order in $1/Q^2$ we can identify x_{Bj} with the fraction of momentum $x = (k^0 + k^z)/(p^0 + p^z)$ carried by a quark or anti-quark in the proton. As discussed by Eisele at this conference, the weak and electromagnetic structure functions of the proton can be measured at HERA inside the kinematic range $10 < Q^2 < 10^5\ GeV^2$, $10^{-4} < x < 1$. In addition, one has the capability at HERA of studying polarized electron – proton collisions, tagged photon reactions, and semi-inclusive diffractive events, $ep \to epX$. The ability to accelerate deuteron beams at HERA will also allow the study of proton-neutron structure function differences.

The central focus of the HERA experiments will be the measurement of the gluon and quark structure functions of the proton. The gluon distribution can be determined by two methods in electroproduction:[1] (1) via the logarithmic variation of the longitudinal structure function F_L, and (2) by measurements of jet photoproduction and inclusive J/ψ photoproduction, cross sections which are predicted to be dominated by the $\gamma g \to q\overline{q}$ hard subprocesses. The charm and beauty structure functions of the proton can be identified by flavor tagging of the recoil quark jet, as well as beam jet correlations. Knowledge of the quark and gluon distributions at small x is crucial for predicting large momentum and heavy quark phenomena at the high energy pp colliders, LHC and SSC.

In many ways, the small $x \lesssim 10^{-4}$ moderate Q^2 regime is the "last frontier" of perturbative QCD. As outlined by E. Levin, A. Mueller, and M. Ryskin at this meeting, the growth of the gluon and quark distributions predicted by QCD evolution must saturate because of unitarity. The high density of the gas of quarks and gluons seen by the electron at small x requires one to consider mutual interactions of the partons within the nucleons. These physical processes restore unitarity but they are inevitability higher–twist and involve new issues in QCD such as correlation lengths and new types of graph resummation.

By definition, small x implies a large rapidity gap ($y_q - y_p = \log \frac{k^0+k_z}{p^0+p^z} = \log x$) between the proton and the struck quark. Physically, for $y \gtrsim 10$, any correlation between the struck quark and the bound-state structure of parent–hadron must be minimal. Thus in the

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small x regime, the deep inelastic scattering cross section measures the myriad number of "extrinsic" subprocesses associated with high energy multi-particle production, and thus has less sensitivity to the bound-state structure of the proton itself. Nevertheless, despite the extraordinarily large rapidity separation between the struck quark and the proton, the QCD predictions for the quark and gluon distributions, $G_{i/p}(x,Q^2)$, $i = g, u, \overline{u}, \ldots$ retain significant dependence on the initial boundary conditions for the $G_{i/p}(x,Q_0^2)$ distributions at the hadronic scale. A fundamental theoretical issue is how these input distributions are related to the non-perturbative bound state structure of the proton itself. The open questions relate not only to the initial distributions of the valence quarks, but also the distribution of gluons and "intrinsic" heavy quarks in the wavefunction of the proton.

One of the central issues in testing logarithmic QCD evolution is the phenomenological importance of higher twist contributions. Recent analyses[2] combining SLAC and BCDMS $e-p$ and $\mu-p$ data give strong evidence for the presence of $1/Q^2$ contributions to the proton structure function which increase monotonically at large x. These contributions signal coherent multi-quark contributions which can carry a large fraction of the nucleon's momentum. Also, as emphasized by Landshoff at this meeting, $F_2(x,Q^2) \Rightarrow \frac{Q^2}{4\pi^2\alpha}\,\sigma_T(x,Q^2)$ must vanish as $x \rightarrow 0$. On the other hand, the Regge behavior of the leading-twist non-singlet structure functions dictates the $x \rightarrow 0$ behavior of $F_2(x,Q^2)$. A form that incorporates these continuity constituents is

$$F_2^{\rm val}(x,Q^2) = 1.33x^{0.56}(1-x)^3\left(\frac{Q^2}{Q^2+0.85\,GeV^2}\right)^{0.44} .$$

The presence of the scale 0.85 GeV^2, as required by continuity with the real photon cross section, implies significant higher twist contributions at low to moderate values of Q^2. Landshoff, in fact, finds that one can largely account for the Q^2 dependence of $F_2(x,Q^2)$ of the present data using the above parameterization, diminishing the role of logarithmic Q^2 evolution in the low x domain. It is clear that a correct treatment of scale-breaking effects must take into account both non-leading twist power-law corrections and logarithmic evolution. Determinations of QCD scale $\Lambda_{\overline{MS}}$ which do not allow for such higher twisting terms invariably overestimate the magnitude of logarithmic evolution and thus overestimate the value of $\Lambda_{\overline{MS}}$.

The Gluon Structure Function

The gluon structure function of the proton is both of extraordinary theoretical interest and is a key input for predictions at hadron colliders. If one sums the leading double logarithms (derived from ladder diagrams, ordered in light cone fractions x, as well as transverse momentum), then one obtains the asymptotic form[3]

$$xG_{g/p}(x,Q^2) \propto \exp\sqrt{\frac{C_A}{\pi b}\ell n(1/x)\ell n\ell n(Q^2/\Lambda^2)}.$$

where $C_A = 3$, and $b = 11 - \frac{2}{3}n_f$. This fundamental prediction of the QCD evolution equations implies a perpetually increasing growth of the gluon distribution and the number of gluons per proton as $x \rightarrow 0$.

One interesting consequence of the monotonic growth of the gluon distribution is the large value of the inelastic $\nu - p$ scattering cross section at the energies of cosmic ray neutrinos $E_\nu^{\rm lab} \cong 10^8\,TeV$ from supernova. As noted by McKay and Ralston,[4] the total neutrino cross section is sensitive to gluons at $x \cong 10^{-8}$, and thus $\sigma_{\nu N}$ is predicted to rise to $\sim 10^{-31}\,cm^2$ at these energies. (The effects of gluon saturation can be neglected here since $Q^2 \sim M_W^2$.)

A considerable number of new analytical results have been obtained for the QCD structure functions for large Q^2 and small x using leading and next-to-leading logarithm summations and recursion. The theoretical developments were pioneered by L. Lipatov, E. Levin, and

M. Ryskin, and by A. Mueller. A sketch presented by Levin of the different regimes in which results are known is shown in Fig. 1.

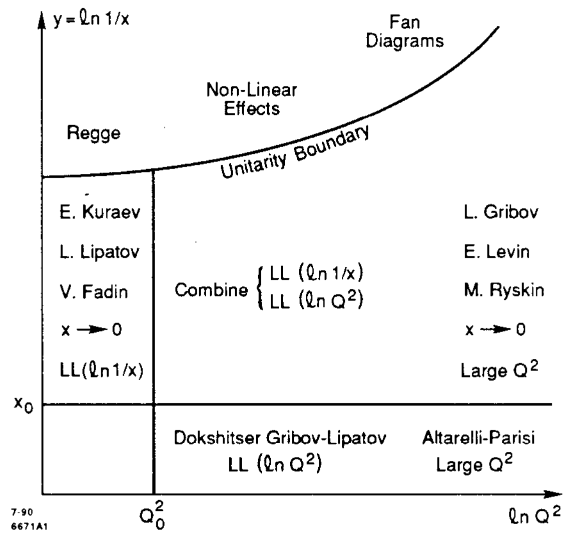

Figure 1. Theoretical regimes for deep inelastic structure functions.

In the $x > x_0$ regime, one can use the usual Gribov–Lipatov–Dokshitser–Altarelli–Parisi evolution. However, at finite Q^2, i.e., $Q^2 < Q_0^2$ and $x \to 0$, one is confronted with summing the same type of QCD–Regge diagrams which control total cross sections. Thus the physics at small x represents a transition between the usual perturbative QCD at moderate x and the microscopic structure of the Pomeron. In particular, Lipatov has shown that the dominant multi-gluon exchange diagrams controlling the fixed Q^2 structure functions are equivalent to the effective exchange of two Reggeized gluons in the t–channel. Results for leading logarithms in this regime were obtained by Kuraev, Lipatov, and Fadin.[5] The summation of leading logarithms in the complimentary $x \to 0$, $Q^2 > Q_0^2$ regime was obtained by Gribov, Levin, and Ryskin.[6]

The summation of leading–twist leading–logarithmic $\ell n^p \frac{1}{x}\, \ell n^q \frac{1}{x}$ corrections to deep inelastic structure functions has the general form

$$xF(x,Q^2) = \sum_n \overline{\alpha}_s^n\, \ell n^{n-1} x \sum_{m=1}^{n} C_{nm} (\ell n Q^2)^m (\ell n x)^{n-m} \,.$$

As discussed in the talks by Marchesini and Webber,[7] these leading contributions can be simulated numerically by computer algorithms which incorporate angle–ordered gluon emission plus terms obtained from virtual loop corrections – referred to as the "non–Sudakov" form factor. This combination of mechanisms has the net effect that triple logarithmic terms of order $\overline{\alpha}_s{}^2 \ell n Q^2\, \ell n^2(1/x)$ cancel (consistent with the Lipatov equation), so that the running coupling constant α_s is effectively kept in the perturbative domain. The results of the computer simulation agree to high accuracy with those obtained from Lipatov's equation. The advantage of the numerical analysis is that one can compute not only structure function evolution, but also details of the induced gluon multiplicity distribution.

The general theory of Regge behavior for high energy reactions in field theory has progressed markedly over the last few years. In his contribution to this meeting, Lipatov discussed recent progress on understanding Pomeron and Odderon ($C = -1$) contributions and the Reggeization of the gluon in QCD in terms of conformally invariant solutions of a one–dimensional Bethe–Salpeter type equation. In related work, the origin of Regge and Pomeron behavior in asymptotically free ϕ^3

theory in SLC dimensions has been worked out explicitly by Kirschner and Lipatov.[8] In his talk at this meeting, Levin discussed the boundaries in $\log 1/x$ and $\log Q^2$ regime where unitarity or saturation corrections set in. I will return to this topic below.

Leading Twist Predictions at Small x

Detailed predictions for the perturbative gluon and quark distributions of the proton based on the leading twist QCD analyses were presented by Bartel, Collins, Krawczyk, Kwiecinski, Schuler, Stirling, Strozik-Kotlorz, and Tung. The general conclusion is that the predictions for the gluon and quark distributions at HERA energies have large numerical uncertainties due to the presently ambiguous knowledge of the input gluon distribution $G(x, Q_0^2)$ At the lowest ranges of x accessible at HERA, the predictions are uncertain by an order of magnitude. Uncertainties due to yet uncalculated higher order corrections to the evolution equations are estimated to be of order 20%. Tung and Stirling have emphasized that the cross section for $pp \to ZX$ at SSC energies and at large rapidity depend particularly strongly on the input form of the gluon distribution. Photoproduction of the J/ψ at HERA energies is similarly dependent on the assumed input shape $G(x, Q_0^2)$. Tung has shown that the leading $x \to 0$ behavior of the input form $G(x, Q_0^2) = C\, x^{A_1}(1-x)^{A_2}\ell n^{A_3}[1 + (1/x)]$ is effectively stable (independent of Q_0) if $A_1 \cong -0.26$.

The sensitivity of the prediction at HERA energies due to different types of leading logarithmic approximations to QCD evolution was discussed in detail by Krawczyk and Kwiecinski. For $x = 0.01$ the predictions based on summing just the leading double logarithms may lead to overestimates of the gluon distribution by an order of magnitude. However, the next-to-leading order results are fairly independent of whether one systematically improves standard Q^2-evolution formula at low x, or uses the Lipatov approach.

Unitarity Constraints

The continuous increase of the gluon structure function, as predicted by PQCD, combined with the QCD factorization theorem, implies that hard-scattering contributions to the hadron-hadron cross section will eventually violate the Froissart bound at sufficiently high energy. For example, when $G(x_1, Q)\; G(x_2, Q)\; [\pi\alpha_s^2/Q^2]$ becomes of order 1, then the predicted lowest order differential cross-section $d\sigma/dx_F$ for the production of dijets or heavy quark pairs with pair mass greater than the scale Q^2 will eventually exceed the projected pp total cross-section at $s = Q^2/x_1x_2$. Thus $\alpha_s G(x, Q)$ must effectively saturate and not grow as fast as RQ, in hadronic collisions. Similarly, as discussed by Mueller and Levin at this meeting, unitarity constraints for electroproduction (from $\sigma(gp \to q\bar{q}x)$) restricts $\alpha_s G < R^2Q^2$ at fixed Q^2 and small x. In each case, the scale R^2 is related to the square of the correlation length of gluons in hadrons. Mueller presented several physical models in both QED and QCD for gluon saturation, in which one can understand physically the impact space correlation scale for gluon source overlap. The unitarity condition is most constraining at low Q. As emphasized by Mueller, the constraint of unitarity becomes numerically severe if one assumes that the gluons in the proton wavefunction are closely correlated in impact space so that R is small—the "hot spot model." HERA energies should be sufficient to test the "hot spot" hypothesis.

The apparent violation of unitarity in PQCD only occurs if we restrict ourselves to leading twist contributions of QCD. For example, when $\alpha_s G$ becomes large, of order R^2Q^2, in small x electroproduction, one clearly cannot neglect higher twist contributions of order $\alpha_s G^2/(R^2Q^2)$ compared to G. We can see how such corrections arise by considering virtual Compton diagrams such as the type of Fig. 2.

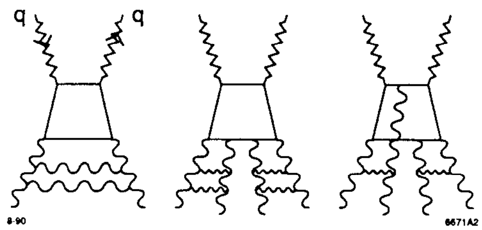

Figure 2. Quark-loop contributions to the virtual Compton amplitude. The fan diagrams (b) and (c) yield higher twist contributions required by unitarity.

The usual leading logarithmic contribution to leading twist evolution arises when the loop integration variable in the quark-loop diagram of Fig. 2a, is in the domain $\ell^2 \ll Q^2$. When $\ell^2 \sim O(Q^2)$, one obtains a higher order correction in $\alpha_s(Q^2)$. When $\ell^2 \sim O(Q^2)$, the "fan" diagrams (b) and (c) are suppressed (in physical gauge) by powers of $1/Q^2$. However, we have seen that if $\alpha_s G/(R^2Q^2)$ is of order 1 at small x, these higher twist contributions cannot be ignored. As noted by Levin, in the regime $\ell^2 \sim O(Q^2)$, one is dealing as with a hard-scattering process controlled by both the photon and proton structure functions.

Thus leading twist PQCD will finally meet its demise in low x fixed Q^2 electroproduction. Model estimates by Bartels, Schuler, and Blumlein, which were presented by Schuler at this meeting indicate that these saturation effects will show up in the kinematic domain accessible by HERA. They find that at $x = 10^{-4}$, $Q^2 = 10^4\, GeV^2$. the saturation effect reduces the magnitude of the gluon distribution by a factor of 2, with the effect quickly growing to an order of magnitude at $Q^2 = 10\, GeV^2$. Thus unitarization is expected to be a highly significant effect at HERA energies. It would clearly be desirable to extend measurements to the regime $1 < Q^2 < 10\ GeV^2$ in order to clearly identify the saturation phenomena.

In the case of hadron-hadron collisions, multiple hard scattering processes such as double pair production $[\sigma = \frac{\sigma_1\sigma_2}{\pi R^2}]$ become important when $\alpha_s^2 G^2 = O(R^2Q^2)$ Thus multi-hard processes in the same event become competitive with single hard-scattering reactions at $s \gg Q^2$. Higher twist multiple interaction contributions of this type were discussed at the meeting by Treleani.

It is interesting to note that the same diagrams that unitarize the electroproduction theory also give in leading twist shadowing of the nuclear structure functions.[9]

Diffractive Hard Processes

In addition to deep inelastic scattering, among the most important high energy reactions to be measured at HERA are the diffractive reactions

$$\gamma^*(Q^2)p \to \mathcal{M}p' \ .$$

In these reactions, the recoil proton is detected in the proton fragmentation region separated by a large rapidity gap from the photon's diffractive system $\mathcal{M}$. Of particular interest is the large Q^2, large $\mathcal{M}^2$, fixed $t = (p' - p)^2$ region where one can isolate the perturbative QCD Pomeron coupling in the t-channel to the $\gamma^* \to q\bar{q}$ amplitude. The phenomenology of such reactions[10] was reviewed at this meeting by Ingelman. It is also important to study exclusive diffractive events such as $ep \to ep\rho$ as a function of the photon mass, the momentum transfer to the proton, and the photon-ρ polarization correlation.

A beautiful perturbative QCD analysis of hard diffractive reactions was presented to the conference by Ryskin. One finds that the two-gluon exchange contributions are controlled by a correlation function $x\, D_N^G$ sensitive to the $q\bar{q}$ di-jet transverse momentum: ($x = 1 - x_F$)

$$\frac{d\sigma}{dq_\perp^2 dx} \sim \frac{1}{q_\perp^4} \left[x D^G(x, q_\perp^2) \right]^2 ,$$

giving an experimental measure of the same quantity which enters the calculation of gluon saturation. In addition, one can analyze the t-dependence of hard diffraction and form factor associated with the pomeron–nucleon–nucleon coupling. In principle, this form factor could have a different fall-off than the electromagnetic form factor of the nucleon because of the Pomeron's underlying multi–gluon structure. On the other hand, in the hard-Pomeron model of Donnachie and Landshoff,[11] the two form factors have the same form. These questions on the structure and coupling of the hard pomeron highlights the importance of tagging the diffracted proton over a large range of kinematics in t.

Generalized Factorization

Given the structure functions determined at HERA, in principle, one can systematically predict all of the hard–scattering cross–sections for the high energy hadron colliders. However, as we have seen, there are theoretical uncertainties on how to isolate the leading twist contributions free from saturation effects.

Recently Collins and Ellis[12] and Catani et al.[13] have extended Lipatov's formalism to connect leading twist deep inelastic lepton scattering results to massive quark pair production in pp and γp collisions through generalized factorization theorems. The new results are based on a t–channel integral ladder–graph equation for the hard–scattering cross section. Numerically one finds that the Born cross section (e.g. for $\gamma g \to Q\overline{Q}$) is drastically modified at low $x = 4M^2/\widehat{s}$ due to the presence of spin–one gluons in the t–channel in higher order diagrams. This large effect, and its slow logarithmic approach to asymptopia at $x \to 0$, implies that there are invariably large uncertainties in the pp and γp predictions. As discussed by Catani, Ciafaloni, and Hautmann,[14] the corrections in $\log 1/x$ summed to all orders in α_s provide an effective K–factor for the hard scattering cross section. The large transverse momentum dependence of the process can also be predicted.

The Input Gluon and Quark Distribution

The fundamental starting point for QCD evolution are the gluon and bound–quark distributions associated with the proton bound–state wavefunction. Logarithmic evolution becomes negligible when Q is comparable to the effective mass of the struck parton in the bound state. At that scale an "intrinsic" gluon distribution persists; it can be identified with the contributions to the effective potential arising from (retarded) gluon exchange

$$G_{g/p}^{\text{Intrinsic}}(x, Q_0^2) = -\left\langle \partial V/\partial M_p^2 \right\rangle \ .$$

A simple analytic model for the intrinsic polarized and unpolarized gluon distribution of the proton, incorporating coherence at low x and spectator–counting rule behavior at $x \to 1$ has been given by Schmidt and myself.[15] In another approach presented to the meeting Glück and Reya have discussed a model for QCD evolution where it is assumed that the anti–quark distribution vanishes and the gluon distribution has the same shape as the valence quark distribution at the starting scale $Q_0^2 \cong 0.2\ GeV^2$. Also, Cudell, Landshoff, and Donnachie[16] have used their hard Pomeron model to compute the non-perturbative low x gluon and sea–quark distributions.

The conventional separation of the proton structure functions into valence and sea components is based on the assumption that contributions to the sea from quarks and anti–quarks are identical. In fact, this assumption cannot be strictly correct because of the Pauli exclusion principle. Schmidt and I[17] have shown that an alternative separation which takes into account identical particle effects ensures that "bound–valence" quark distribution is devoid of Pomeron and Reggeon behavior and vanishes at $x \to 0$. In the case of QCD in one–space and one–time, the quark and sea contributions can be computed numerically diagonalizing the light–cone Hamiltonian.[18] There is also provocative phenomenological evidence, as well as theoretical suggestions for intrinsic strange, charm, and beauty quark distribution associated with the bound-state structure of the proton. The most striking characteristic of the heavy intrinsic quark distributions is their shift to large x since the bound-state wavefunction is maximized when the constituents have equal velocity. HERA will be an ideal laboratory to test for the presence of these exotic QCD components of the nucleon. Two types of experiments will be particularly important: (1) identification of events where a heavy quark recoils against the scattered lepton, together with an associated heavy anti-quark jet in the proton beam direction; and (2) studies of electroproduction events where heavy quarkonium is found at large x_L along the proton direction.

Open Questions

The potential of HERA to probe the domain of small x QCD has exposed many new theoretical questions important both in deep inelastic lepton scattering and at the new high energy colliders. By far the most important question is the nature and possible calculability of gluon saturation. At $x \lesssim 10^{-4}$ and $Q^2 \lesssim 10\ GeV^2$ leading twist QCD is clearly inadequate; just as in the low energy domain, higher twist multi-parton processes must be considered. A systematic treatment is clearly needed for both deep inelastic lepton scattering and hard hadron-hadron scattering processes at small x. Hard diffraction reactions from HERA will provide an important measure of multi-gluon matrix elements.

Despite great theoretical progress, there are still many theoretical uncertainties in the leading twist predictions. In some processes, involving annihilation or spin-one exchange, large higher order corrections to generalized factorization predictions emerge. The predictions for HERA are still very much dependent on the nature of the input quark and gluon distributions, requiring a deep understanding of the interface between perturbative evolution and non-perturbative dynamics.

Expectations from HERA

The range of possible experiments testing fundamentals of QCD at HERA is very broad. In addition to the measurements of gluon and quark structure functions at both small and large x one can use charged current reactions $ep \to \nu X$ and proton-neutron differences to isolate valence-quark dominated contributions, such as $F_3(x, Q^2)$. Several methods can be used to distinguish intrinsic versus perturbatively generated heavy quark contributions to the proton structure functions. The possibility of electron polarization at HERA would a number of interesting spin correlation studies. A deuteron beam at HERA would provide measurements of spin–one structure functions[19] and dynamics beyond the nucleon kinematic limit. If positron beams become available, then a number of asymmetries could be measured, including the determination of the charge–cube of the quarks and the quark-anti-quark difference by studying $e^{\pm}p \to e^{\pm}\gamma X$. The importance of measuring both inclusive and exclusive diffractive events was repeatedly emphasized at the meeting. In addition, there are a whole range of inclusive and exclusive experiments one can do with tagged virtual photon, W, and Z^0 beams at HERA including generalized Compton scattering. All of these reactions are important not only for projecting QCD predictions to higher energies, but also for understanding the basic structure of QCD and the dynamics of the proton itself.

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