

# Leading proton spectrum from DIS at HERA

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The QCD hardness scale for secondary particles ( $h$ ) production in semi-inclusive deep inelastic scattering (DIS),  $ep \rightarrow e' X h$ , gradually decreases from  $Q^2$ , the photon virtuality which determines the hard scale in the virtual photon (current) fragmentation region to a soft, hadronic, scale in the proton fragmentation region. This suggests similarity of the inclusive spectra of leading protons and neutrons,  $h = p, n$ , in high energy hadron-proton and virtual photon-proton collisions. We explore this similarity extending to the DIS regime the nonperturbative peripheral mechanisms of inelastic scattering traditionally used in hadronic interactions to explain fast nucleons production. While the production of leading neutrons is known to be exhausted by DIS off charged pions, the production of leading protons by DIS off neutral pions must be supplemented by a substantial contribution from isoscalar reggeon ( $f_0$ ) exchange extrapolated down to moderate values of  $x_L$ . We comment on the  $x$  and  $Q^2$  dependence of leading proton production as a probe of a universal pattern of the  $x, Q^2$  evolution of the nucleon and meson (reggeon) structure functions at small  $x$ .

In deep inelastic  $ep$  scattering, according to the standard QCD description of hadronization, the proton fragmentation region is very different from the current and/or photon fragmentation region. Namely, the virtuality of partons in generalized ladder diagrams gradually decreases from the hard scale  $Q^2$  of the struck parton in the current fragmentation region to the soft, hadronic, scale of the parent parton in the proton fragmentation region.

Although until quite recently experimental data on proton fragmentation were scarce<sup>1</sup>, presently the ZEUS and H1 leading proton spectrometers (LPS) and forward neutron calorimeters (FNC) are operational and are amassing data on leading proton and neutron production [3,4].

Whereas popular Monte-Carlo implementations of perturbative QCD (Ariadne [5], Herwig [6] and others) are very successful in the photon fragmentation region (for a recent review see [7]), a purely perturbative description of the proton fragmentation region is not yet possible and the current versions of Monte Carlo hadronization models underestimate the yield of fast secondary nucleons [8]. Traditionally, leading proton production in inelastic collisions is modeled via nonperturbative peripheral interactions. Such peripheral models were quite successful when applied to hadronic collisions (for a review see [9]). A well known example of this type of processes is the interaction of projectiles with pions from the chiral mesonic substructure of the proton. We recall that in hadronic reactions, the pion exchange mechanism with absorption exhausts the cross section for the leading neutron production in  $pp \rightarrow Xn$ ,  $\pi n \rightarrow Xp$ ,  $pn \rightarrow Xn$  (see [10] and references therein). There is at present a mounting evidence of the importance of the chiral mesonic substructure of the nucleon also in DIS (see [11] and the reference therein). Here let us mention a successful explanation of

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<sup>1</sup>Before the ZEUS/H1 LPS era, leading protons in DIS have been studied only in the fixed-target bubble-chamber neutrino experiments [1]. Only large values of the Bjorken  $x$  were accessible, leading to a strong kinematical bias in the leading proton spectra [2]. The small- $x$  data from HERA are free of this kinematical bias.

the Gottfried Sum Rule violation (see for instance [12] and references therein <sup>2</sup>) and of the  $\bar{d}$ - $\bar{u}$  asymmetry as seen in  $pp$  and  $pn$  Drell-Yan production [15]. Exactly the same physics opens an exciting possibility to study the pion structure function at HERA. Here one can separate DIS off nearly on-mass-shell  $\pi^+$  by triggering on fast neutrons from semi-inclusive  $ep \rightarrow e'Xn$  reaction [16] (see also [17–19]). In this communication we explore to which extent leading proton production in DIS can be understood quantitatively within peripheral mechanisms.

Following the conventions for diffractive DIS [20], we define the semi-inclusive structure function

$$\frac{d\sigma(ep \rightarrow e'p'X)}{dxdQ^2dzdt} = \frac{2\pi\alpha^2}{Q^2x} \left[ 2 - 2y + \frac{y^2}{1+R} \right] \cdot F_2^{(4)}(z, t, \beta, Q^2). \quad (1)$$

Here  $\alpha$  is the electro-magnetic fine structure constant,  $z$  is the fraction of the light-cone momentum of the beam proton carried by the outgoing proton  $z = \frac{p'^+}{p^+}$  (the same quantity is often denoted by  $x_L$ ),  $t$  is the  $(p, p')$  four-momentum transfer squared,  $x, y, Q^2$  and  $\beta = \frac{Q^2}{M^2+Q^2} = \frac{x}{1-z}$  are the standard DIS variables and  $R = \sigma_L/\sigma_T$ . In the present analysis we focus on leading protons with  $0.6 < z < 0.9$ . In our extension of the peripheral models of fragmentation used in hadronic reactions to lepton DIS at HERA, we consider four mechanisms of leading proton production (Fig. 1): a) diffractive production of protons (pomeron **IP** exchange) which dominates at  $z \rightarrow 1$ , and constitutes a background to fragmentation in non-diffractive DIS at  $z \lesssim 0.9 - 0.95$ ; b) spectator protons from the fragmentation of the  $\pi N$  Fock state of the physical proton produced by DIS off virtual  $\pi^0$  (pion-exchange mechanism); c) protons produced as decay products of fast baryon resonances of which the  $\Delta$  production via pion-exchange is a typical, and predominant, source; d) reggeized heavy meson (reggeon  $R$ ) exchange contribution (predominantly the isoscalar reggeon,  $R = f_0$ , exchange). A preliminary evaluation of the first two mechanisms has been done in [16]. The background

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<sup>2</sup>For related work on electro-magnetic properties of nucleons and  $W$ -boson and jet production in nucleon-nucleon collisions see [13,14].

from pion and reggeon exchange to the dominant pomeron exchange at  $z \gtrsim 0.95$  has been discussed recently in [20–23], and we partially use the results of these works. Diffraction excitation of the proton into high-mass states also contributes to leading proton production, and we shall comment on this small contribution following the considerations in [24].

Under approximations to be specified below, the contributions of all four mechanisms to the semi-inclusive structure function can be written in the factorized form ( $i = \mathbf{IP}, \pi^0 p, \pi\Delta, f_0$ ):

$$F_2^{(4)}(z, t, \beta, Q^2) = \sum_i F_2^{(4)}(i; z, t, \beta, Q^2) = \sum_i f_i(z, t) \cdot F_2^i(\beta, Q^2), \quad (2)$$

where  $F_2^i(\beta, Q^2)$  is the structure function of the exchanged object (pion, pomeron, reggeon),  $f_i(z, t)$  is its flux factor and  $\beta$  is the Bjorken variable for DIS off the exchanged object.

We start our discussion with the pion exchange mechanism. In this case  $F_2^i(\beta, Q^2)$  is the structure function of the physical pion and the flux factor is given by

$$f_{\pi^0 p}(x_\pi, t) = \frac{g_{p\pi^0 p}^2}{16\pi^2} (1-z) \frac{(-t)|F_{\pi N}(z, t)|^2}{(t - m_\pi^2)^2}. \quad (3)$$

Strictly speaking, Eq. (3) holds in the plane wave impulse approximation. A recent analysis [10] has shown that absorption corrections to pion exchange in DIS are small and can be neglected for the purposes of the present analysis. Also, the off-mass shell extrapolation effects are marginal and the on-mass shell pion structure function can be used. Important consistency check is provided by the simultaneous description of the hadronic leading nucleon data. The results for DIS in the interesting region of  $0.6 \lesssim z \lesssim 0.9$  only marginally depend on whether the light-cone or Regge parameterization of  $|F_{\pi N}(z, t)|^2$  are used (for a detailed discussion concerning the choice of the form factor see Refs. [10,12]).

Production of fast  $\Delta$ 's is also known to be dominated by pion exchange. For  $\Delta^{++}$  production the flux factor is given by

$$f_{\pi\Delta}(z, t) = \frac{2g_{p\pi^-\Delta^{++}}}{16\pi^2} (1-z) \frac{((m_\Delta + m_N)^2 - t)^2((m_\Delta - m_N)^2 - t)|F_{\pi\Delta}(z, t)|^2}{6m_N^2 m_\Delta^2 (t - m_\pi)^2}. \quad (4)$$

Contributions from  $\Delta^+$  and  $\Delta^0$  production can be included using the familiar isospin relations (see for instance [12,24]). In the simplest one-pion exchange approximation, the

polarization state of the produced  $\Delta$ 's is such that the  $\Delta \rightarrow \pi N$  the decay angular distribution in the Gottfried-Jackson (t-channel) frame equals:

$$w(\theta_J, \phi_{TY}) = 1/4 \cdot (1 + 3\cos^2\theta_J) \cdot Y_{00}(\phi_{TY}) ,$$

where  $\theta_J$  and  $\phi_{TY}$  are the so-called Jackson and Treiman-Yang angles, respectively. Absorptive correction modify slightly this simple form [25], but these corrections can be neglected for the purposes of the present analysis, since both the  $z$ - and  $t$ - spectra of decay protons only weakly depend on the decay angular distributions.

For the diffractive  $e + p \rightarrow e' + p' + X$  reaction, our semi-inclusive structure function coincides with the pomeron component of the diffractive structure function,  $F_2^{(4)}(\mathbf{IP}N; z, t, \beta, Q^2) = F_{2,\mathbf{IP}}^{D(4)}(z, t, \beta, Q^2)$ . At  $z \lesssim 0.9$ , diffractive DIS is a small background to non-diffractive DIS and a somewhat simplified description is justified. Since the ZEUS data have [3]  $x \lesssim 10^{-3}$  and  $z \lesssim 0.9$  then  $\beta$  is quite small,  $\beta \lesssim 2 \cdot 10^{-3} - 10^{-2}$  and it has been argued [26,27] that at such a small  $\beta$  one expects the factorization

$$F_2^{D(4)}(z, t, \beta, Q^2) = f_{\mathbf{IP}}(z, t) \cdot F_2^{\mathbf{IP}}(\beta, Q^2) . \quad (5)$$

The normalization of the pomeron flux factor  $f_{\mathbf{IP}}(z, t)$  and the pomeron structure function  $F_2^{\mathbf{IP}}(\beta, Q^2)$  is a matter of convention, and only the product of the two is well defined. To be specific, we use the triple-Regge parameterization for the flux factor

$$f_{\mathbf{IP}}(z, t) = \frac{1}{8\pi^2(1-z)} (1-z)^{2(1-\alpha_{\mathbf{IP}}(t))} G_{\mathbf{IP}}(t), \quad (6)$$

where  $G_{\mathbf{IP}}(t) = G_0 \exp(B_{\mathbf{IP}}t)$  with  $G_0 = 21.2$  mb [21–23] from the Regge decomposition of the NN total cross sections [28] and  $B_{\mathbf{IP}} = 3.8 \text{ GeV}^{-2}$  according to the triple-Regge analysis of hadronic diffraction scattering [9,29–31]. For  $z \lesssim 0.9$ , the specific Regge effects coming from  $(1-z)^{2(1-\alpha_{\mathbf{IP}}(t))}$  and from the  $t$ -dependence of the pomeron trajectory  $\alpha_{\mathbf{IP}}(t)$  are marginal and, besides the standard factor  $\frac{1}{1-z}$ , the main  $z$  dependence of the flux comes from the kinematical boundary  $|t| \geq |t|_{min} = \frac{m_p^2(1-z)^2}{z}$  in the form factor  $G(t)$ . In principle  $F_{2,\mathbf{IP}}^{D(4)}(z, t, \beta, Q^2)$  can be derived from experimental data on diffractive DIS, but currently

for  $\beta \lesssim 2 \cdot 10^{-3} - 10^{-2}$  the pomeron structure function stays basically unknown. It has been argued, [26], that at small  $\beta$  the conventional DGLAP evolution holds for the pomeron structure function giving a  $\beta$ , and  $Q^2$  dependence of  $F_2^{\text{IP}}(\beta, Q^2)$  similar to that of  $F_2^\pi(\beta, Q^2)$  (see for instance [27]). On the other hand, the triple-pomeron formula with soft pomerons gives the scaling prediction  $F_2^{\text{IP}}(\beta, Q^2) = C_{\text{IP}}\beta^{-0.08}$  (the normalization  $C_{\text{IP}} = 0.026$  has been fitted [23] to the H1 experimental data [20]). We use these two models to check the sensitivity of the leading proton spectra to the evolution in  $\beta$  and  $Q^2$ .

The reggeon exchange is an important ingredient of the triple-Regge phenomenology of hadronic diffraction, although its strength is not very well known [9,29,30]. The triple-Regge parameterization for the reggeon flux is

$$f_R(z, t) = \frac{1}{8\pi^2} (1 - z)^{1-2\alpha_R(t)} G_R(t) , \quad (7)$$

where  $\alpha_R(t)$  is the reggeon trajectory. We take  $G_R(t) = G_R(0) \cdot \exp(B_R t)$ , where for the dominant  $f_0$ -exchange  $G_R(0) = 76$  mb [21,23] and  $B_R = 4$  GeV $^{-2}$ , which is consistent with the data on leading proton production in  $pp$  collisions [32]. Triple-Regge considerations in conjunction with fits to the NN total cross sections [28] suggest the isovector reggeon exchange to be much weaker than the isoscalar  $f_0$  exchange [21,23]. The reggeon structure function is basically unknown. The extension of microscopic analysis [26] to reggeons suggests that the  $\beta$  and  $Q^2$  dependence of this structure function at small  $\beta$  must be similar to that of the pion structure function,  $F_2^R(\beta, Q^2) \sim F_2^\pi(\beta, Q^2)$  and/or the pomeron structure function,  $F_2^R(\beta, Q^2) \sim F_2^{\text{IP}}(\beta, Q^2)$ . Arguably the gross features of the small- $\beta$ , large- $Q^2$  behavior of  $F_2^i(\beta, Q^2)$  should be similar for all targets  $i$ . If the extrapolation along the Regge trajectory to the particle pole  $t = m_{f_0}^2$  were possible, one could have related  $F_2^R(\beta, Q^2)$  to the  $f_0$  meson structure function, which at small  $\beta$  is expected to be similar to  $F_2^\pi(\beta, Q^2)$ . Going from the particle pole  $t = m_{f_0}^2$  to the scattering region  $t < 0$  brings the off-mass shell suppression in, and it is natural to expect  $F_2^R(\beta, Q^2) < F_2^\pi(\beta, Q^2)$ . The triple-Regge phenomenology of hadronic diffraction suggests the suppression factor  $\lambda_f \sim 0.5$  with a large uncertainty [21] (because of different normalization of the flux in [21] and [23], the estimate of  $\lambda_f$  in [21] must

be taken with the factor  $\frac{\pi}{2}$ ). Similarly to the pomeron structure function, the triple-Regge formalism with soft pomerons gives the scaling  $F_2^R(\beta, Q^2) = C_R \beta^{-0.08}$ . Eventually, with high precision data on diffractive DIS, one would be able to evaluate  $F_2^R(\beta, Q^2)$  directly from the reggeon background to pomeron exchange at  $z \gtrsim 0.95$ .

The single particle inclusive  $(z, t)$ -spectrum of protons is defined as  $R(z, t, x, Q^2) = F^{(4)}(z, t, \beta, Q^2)/F_{2p}(x, Q^2)$ . A fully differential study of  $R(z, t, x, Q^2)$  is not yet possible with the limited statistics of the preliminary ZEUS data [3]. The data were collected within the following experimental cuts  $\Omega_{exp}$ :  $0.6 < z < 0.9$ ,  $|t|_{min} < |t| < 0.5 \text{ GeV}^2$ ,  $10^{-4} < x < 10^{-3}$  and  $4 < Q^2 < Q_{max}^2$ , where  $Q_{max}^2$  is the maximal kinematically attainable  $Q^2$ . Within these cuts the fraction of events with leading proton is given by:

$$R_{exp} = \sum_i R_{exp}^i = \sum_i \frac{\Delta\sigma^i(\Omega_{exp})}{\Delta\sigma^{tot}(\Omega_{exp})}, \quad (8)$$

where

$$\Delta\sigma^i(\Omega_{exp}) = \int_{z_{min}}^{z_{max}} dz \int_{t_{min}}^{t_{max}} dt \int_{x_{min}}^{x_{max}} dx \int_{Q_{min}^2}^{Q_{max}^2} dQ^2 \frac{d\sigma^i}{dxdQ^2dzdt}, \quad (9)$$

$$\Delta\sigma^{tot}(\Omega_{exp}) = \int_{x_{min}}^{x_{max}} dx \int_{Q_{min}^2}^{Q_{max}^2} dQ^2 \frac{d\sigma^{tot}}{dxdQ^2}, \quad (10)$$

and the subscript  $i$  stands for one of the mechanisms shown in Fig.1.

As emphasized above, the pion, pomeron and reggeon structure functions are unknown in the  $\beta$  region considered in our present analysis. For a reference evaluation of  $R_{exp}^i$ , we take the GRV parameterization for the  $(\beta, Q^2)$  evolution of the pion structure function [33], the flux of pions evaluated in the light-cone model for the chiral structure of the nucleon [12] (the Regge parameterization leads to very similar result [10]) and the triple-Regge model parameterization  $F_2^{\text{IP}}(\beta, Q^2) = 0.026 \beta^{-0.08}$  described above. For the proton structure function, which enters the evaluation of the denominator (10) of the ratio (8), one can use any convenient fit to the HERA data. In the present analysis we take the GRV parameterization [34]. The practical calculations have been performed with a Monte Carlo implementation of the above formalism. As a result of our analysis, we find  $R_{\pi^0 p}(\Omega_{exp}) = 2\%$ ,

$R_{\pi\Delta}(\Omega_{exp}) = 0.9\%$  and the tail of the pomeron exchange contribution [22] gives  $R_{\text{IP}p}(\Omega_{exp}) = 1.2\%$ , so that  $R_{1+2+3}(\Omega_{exp}) = 4.05\%$ . Note that QCD hadronization models (Ariadne, Herwig) were never meant to describe the nonperturbative proton fragmentation region; for example Ariadne [5] gives  $R(\Omega_{exp})$  in the per mill range and a similar under-prediction for the production of leading neutrons [8]. From the comparison with the ZEUS experimental result,  $R_{exp}^{ZEUS} = 9.2 \pm 1.7\%$  (stat. only) [3], we conclude that about 5 % of the missing strength must be attributed to the reggeon exchange. In the triple-Regge scaling model,  $F_2^R(\beta, Q^2) = C_R \beta^{-0.08}$ , this requires  $C_R = 0.12$  within a factor of 1.5 uncertainty.

The importance of different mechanisms can be better seen from the  $z$ -dependence of the ratio  $R_{exp}(z)$  defined for the experimental  $(t, x, Q^2)$  range as shown in Fig. 2. Clearly the importance of the reggeon exchange can be seen from the figure. With the set of parameters specified above, the reggeon contribution makes  $R_{exp}(z)$  approximately flat at  $z \lesssim 0.9$ , in close similarity to a flat  $z$ -spectrum of leading protons in hadronic interactions [32]. The preliminary H1 results are also consistent with the flat  $z$ -spectrum [4].

The  $z$ -spectrum of leading nucleons from diffraction double dissociation (DD) has been studied in [24]. It can be isolated experimentally by the rapidity gap (GAPCUT) selection method [3]. An extension of the analysis [24] to leading protons shows that  $\sim 70\%$  of DD events have leading protons, mainly produced by excitations of the  $N\pi\pi$  and high mass continuum states. Roughly  $\sim 50\%$  of final state protons have  $z > 0.6$ . Since DD constitutes  $\sim 2\%$  of the DIS events, only  $\sim 0.7\%$  have a leading proton with  $z > 0.6$  generated by this mechanism. DD is therefore a small,  $f(\text{GAPCUT}) = R_{DD}(\Omega_{exp})/R_{exp} \sim 7\%$ , background to the dominant non-diffractive production mechanism, in good agreement with the ZEUS findings. The LEPTO6.5 ‘soft color interaction’ model [35] which, unlike Ariadne and/or Herwig, is supposed to describe all aspects of DIS including leading proton production, over-predicts the fraction of GAPCUT events:  $f(\text{GAPCUT}) \approx 20\text{-}30\%$ . The observed leading proton  $z$ -distribution of the GAPCUT sample [3] is also consistent with the  $z$  spectrum of protons generated in proton dissociation into  $N\pi\pi$  and continuum states as shown in Fig. 2 of [24]. It can readily be included in the analysis of higher precision data.

This evaluation of the reggeon exchange from fragmentation into protons at  $z \lesssim 0.9$  is consistent within a factor of 2 with estimates of the reggeon background to pomeron exchange in the diffractive region of  $z \gtrsim 0.95$  [23]. A caveat in comparing these two extreme regions is the possible reggeon-pomeron interference contribution  $\sim \frac{1}{\sqrt{1-z}}$ , which can be substantial in the diffractive domain and small in the fragmentation region  $z \lesssim 0.9$ . A combined analysis of high precision fragmentation and diffractive data would be the best way to fix the reggeon-pomeron interference contribution, but such an involved phenomenology is not warranted with the presently available data. Note also that the ZEUS data are preliminary and lacking the evaluation of systematic errors.

In Fig. 3 we show the slope  $b(z)$  of the  $t$ -distributions defined in the experimental range of  $(x, Q^2)$  ( $R(z, t) \propto \exp(b(z)t)$ ). The slope of the reggeon trajectory is large,  $\alpha'_R = 0.9 \text{ GeV}^{-2}$ , and for pure reggeon exchange contribution quite a substantial rise of the slope is expected:  $b_R(z) = B_R + 2\alpha'_R \log \frac{1}{1-z}$ . Similar growth of the slope is expected also for the pion exchange contribution. The increase of the slope at large  $z$  is tamed by the small diffraction slope of the pomeron contribution. The parameter  $B_R$  is poorly known and the leading proton spectrum offers the best possibility for its determination. Our results for  $b(z)$  obtained with  $B_R = 4 \text{ GeV}^{-2}$  are close to the slope of the  $t$ -dependence for leading protons observed in  $pp$  collisions [32].

The  $(x, Q^2)$ -dependence of different mechanisms is controlled by the ratios  $\rho_i(x, Q^2) = F_2^i(\frac{x}{1-z}, Q^2)/F_{2p}(x, Q^2)$ . In the scenario with the scaling soft pomeron/reggeon structure functions,  $\rho_{\text{IP},R}(x, Q^2)$  decreases with rising  $Q^2$  and/or decreasing  $x$ , because of the scaling violations and steep  $x$ -dependence of the proton structure function  $F_{2p}(x, Q^2)$ . Fig. 4 shows that in such a scaling scenario (no QCD evolution for  $F_2^{\text{IP},R}(\beta, Q^2)$ ), one would expect significant dependence of the leading proton production on both  $x$  and  $Q^2$ . On the other hand, if  $F_{\text{IP},R}(\beta, Q^2)$  satisfies the conventional  $(\beta, Q^2)$  evolution at small  $\beta$  [26], one would expect very weak  $(x, Q^2)$  dependence of the leading proton spectrum. This stays true also in the real photoproduction limit. In the present analysis we model the evolution effects by taking  $F_2^{\text{IP},R}(\beta, Q^2) = \lambda_{\text{IP},R} f_2^\pi(\beta, Q^2)$  with the GRV pion structure function. We adjust

$\lambda_{\text{IP}} = 0.2$  and  $\lambda_f = 0.5$  as it was evaluated in [21] so that we reproduce the same  $R_{\text{exp}}^i$  as with the scaling (no evolution) scenario within the ZEUS kinematical cuts.

In the conventional evolution scenario we indeed find a very weak  $x$  and  $Q^2$  dependence of the leading proton spectra. The preliminary ZEUS data [3] better agree with this scenario, although the error bars are still rather large. The preliminary H1 data [4] on the  $t$ -integrated  $F_2^{(4)}(z, t, x, Q^2)$  also support the conventional evolution scenario.

We conclude that the salient features of fragmentation into leading protons can be understood quantitatively in terms of peripheral mechanisms extended to the DIS regime. The experimentally observed similarity of the leading proton spectra in  $pp$  collisions and  $ep$  DIS is a natural consequence of these mechanisms. We emphasize that our approach has the capability of a unified description of diffractive DIS at  $z \gtrsim 0.9$  and of fragmentation into protons in non-diffractive DIS. Of the four sources of leading protons pion exchange can be experimentally determined using neutron tagged DIS. Experimental confirmation of our estimate for this process will lend strong support also for our evaluation of the  $\Delta$  contribution. The pomeron exchange background can be inferred from diffractive DIS. Finally, the reggeon exchange mechanism of fragmentation can also be tested in diffractive DIS. The combined analysis of the high precision leading proton data and diffractive DIS data makes possible a determination of the reggeon-pomeron interference effects, which has not been accomplished with the hadronic diffraction data [9,29,30].

A comparison of the soft pomeron no-evolution (unrealistic though it is) and conventional evolution scenarios for the reggeon structure function shows that the high precision leading proton spectrum offers an interesting test of the universality of the QCD evolution properties of structure functions at small  $x$  (For a related discussion of the pion exchange mechanism within Veneziano's fracture function [36] context see [37].).

We conclude with the comment that similar fragmentation mechanisms may be at work also at smaller  $z$ , where DIS on the multi-pion Fock states of the physical nucleon,  $(n\pi)N, (n\pi)\Delta, (n\pi)N^*, (n\pi)\Delta^*$ , provides a natural mechanism for slowing down secondary protons. In the spirit of the above discussion, the weak  $x, Q^2$  dependence must hold also

for slower protons. Similar arguments hold for the fragmentation of protons into hyperons ( $\Lambda, \Sigma, \dots$ ).

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## Figure captions

Fig.1

Peripheral mechanisms of leading proton production.

Fig.2

The fraction (in per cent) of DIS events with a leading proton in a given  $z$  bin ( $\Delta z = 0.03$ ) predicted by our model (thick solid curve) in comparison with the ZEUS preliminary data [3]. The contributions of four mechanisms of Fig. 1 are shown separately: the thin solid line shows the pomeron-exchange contribution, the long-dashed curve is for the pion-exchange contribution, the dashed curve shows protons from the  $\Delta$  production and the dotted curve is for the reggeon-exchange component.

Fig.3

The slope of the  $t$ -distributions predicted by the model is compared with the ZEUS preliminary data [3].

Fig.4a

The sensitivity of the fraction of DIS events containing leading protons within ZEUS cuts to the  $Q^2$  evolution effects for the two different scenarios for the pomeron and reggeon structure function: the curves marked by filled circles are for the no-evolution soft pomeron model, the unmarked curves show the results for the conventional QCD evolution scenario modeled by the GRV pion structure function. The legend of curves is the same as in Fig. 1.

Fig.4b

The same as Fig. 4a, but for the  $x$ -dependence of the fraction of DIS events containing leading protons within ZEUS cuts.

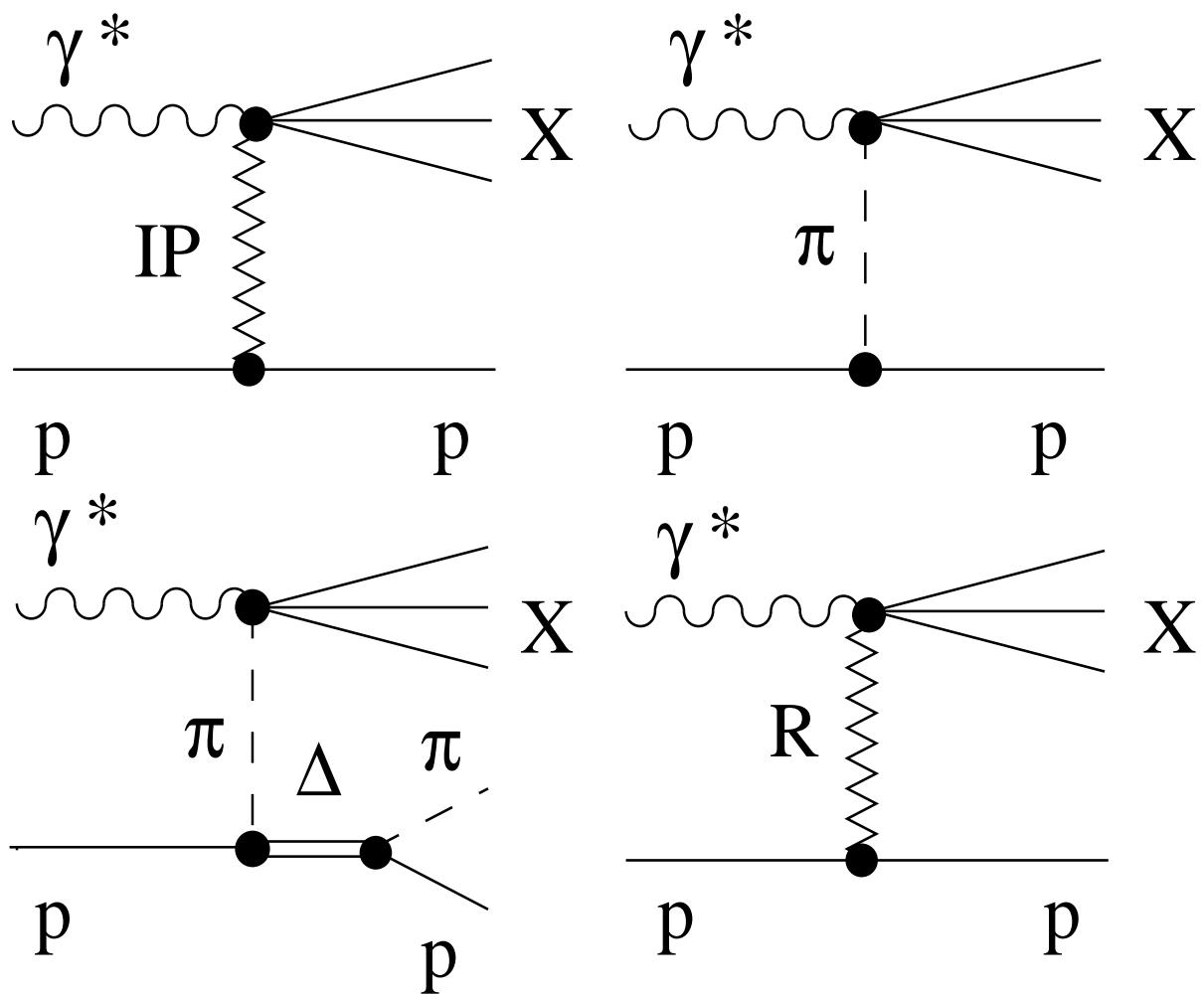


Fig. 1

ZEUS preliminary data

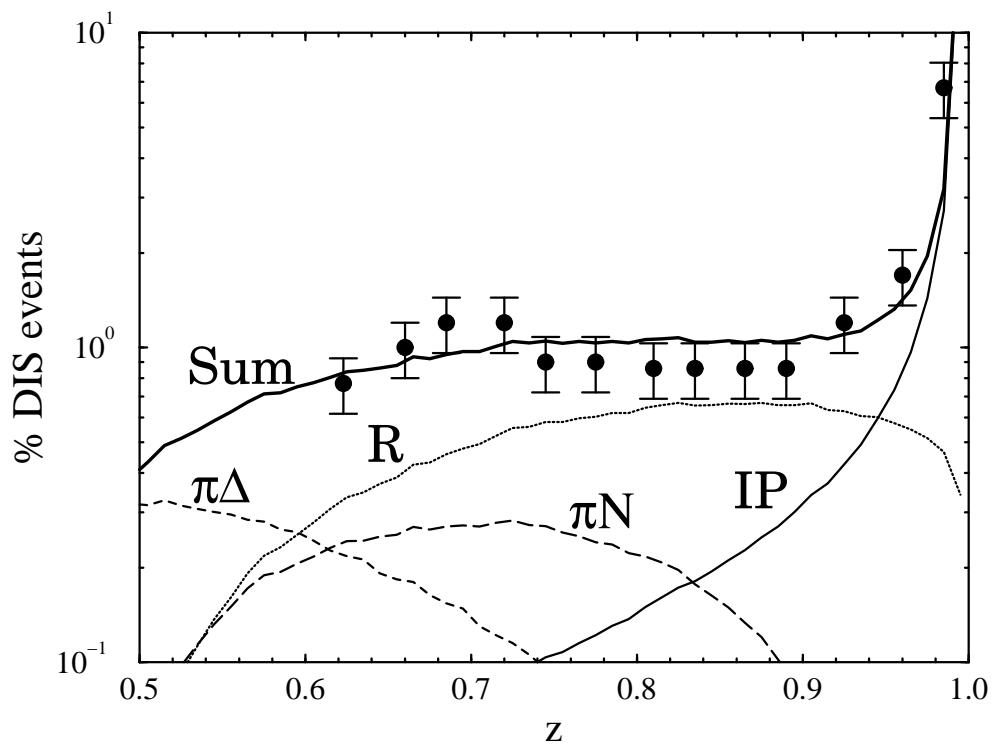


Fig.2

ZEUS preliminary data

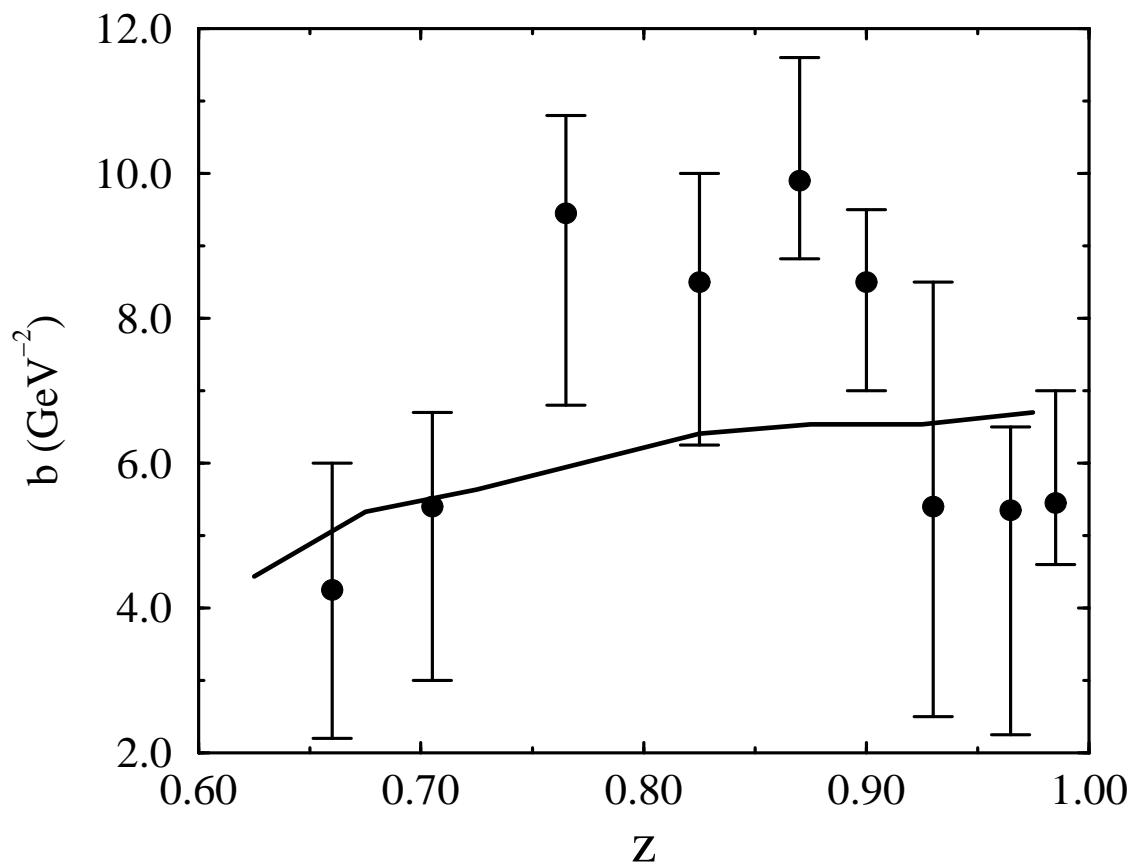


Fig. 3

with ZEUS cuts

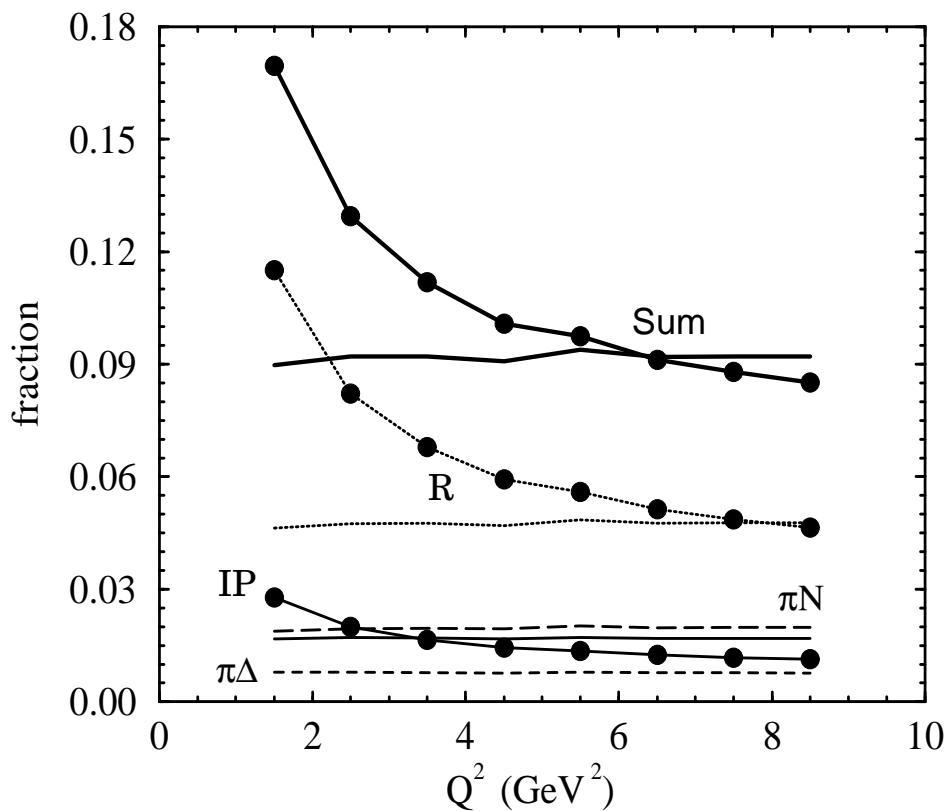


Fig. 4a

with ZEUS cuts

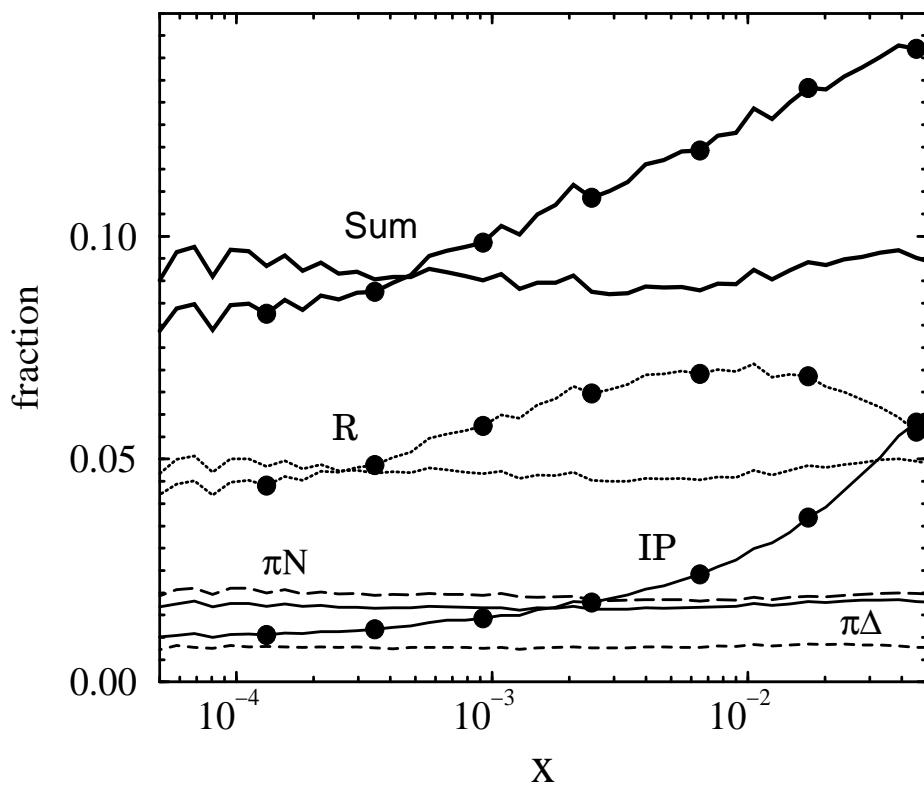


Fig. 4b