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SOFT AND HARD STRUCTURE OF NUCLEONS AS SEEN IN DEEP INELASTIC SCATTERING AT HERA*

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The old idea of using mesons in the nucleon as targets has been revived, developed further and applied successfully to production of leading baryons in deep inelastic scattering at HERA. I present a brief status report of the theory of leading baryon production placing an emphasis on the continuity between soft and hard scattering physics.

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1. Introduction

The perturbative QCD embodied in the DGLAP evolution describes the Q^2 dependence of the proton structure function (SF) starting from, but telling nothing about, the input parton densities at a starting point Q_0^2. The latter depend on the structure of protons and the dynamics of high energy scattering at nonperturbative large distances.

When probed with poor resolution, at small momentum transfer, the behaves as a point like particle which scatters only elastically. At a higher momentum transfer, one starts resolving the meson-baryon core substructure of protons and the knock-out of mesons is an onset of inelastic interaction. At still higher energies and higher momentum transfer one starts resolving the constituent quark substructure of mesons and baryons. Finally, in the regime of deep inelastic scattering one sees the QCD gluon and quark-parton substructure of those constituents.

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The meson-baryon substructure of protons is a bridge between the intermediate energy physics and deep inelastic scattering and provides the necessary input for the DGLAP evolution analysis of DIS. The corollary of this approach developed in Jülich the past several years is that the sea starts with the strongly correlated quarks and antiquarks clustered into states having the quantum numbers of low-lying mesons. One of the highlights is a prediction of the substantial $\bar{d}/\bar{u}$ asymmetry at large x which is the footprint of the flavour composition of low-lying mesons and baryons and couplings between them [1]. This issue has been reviewed at this conference by Speth and Garvey , see also [1]. In my talk I focus on implications for final states in deep inelastic scattering, which were worked out in a series of recent papers by the Cracow-Jülich-Landau group [2–6].

2. From structure functions to final states

The DIS cross section is proportional to the imaginary part of the forward Compton scattering amplitude. Fig. 1(a) shows DIS off valence quarks in the target, which is sensitive to the quark content of the target. It vanishes at small x but is large at intermediate x. The main ingredient here is the quark-antiquark annihilation amplitude which can be related to the unintegrated valence quark density, $A \propto dV(x,k^2)/d\log k^2$. Fig. 1(b) shows DIS off the sea quarks, which for large Q^2 are mostly generated by the DGLAP evolution from the gluons and as such do not depend on the target. The main ingredient in the calculation of this diagram is the unintegrated gluon density function $dG(x,\kappa^2)/d\log\kappa^2$.

The unitarity cuts of QCD diagrams of Fig. 1 give the final states in terms of the produced gluons, quarks and antiquarks. The alchemy of 20th century — the QCD hadronization Monte Carlo codes (HERWIG, ARIADNE, LEPTO,....) — prescribe how these produced colored partons cascade/fuse into colorless hadrons. The principal point about this alchemy is that QCD hardness scale for secondary particles (h) in semi-inclusive DIS, $ep \to e'Xh$, gradually decreases from hard scale Q^2 in the virtual photon (current) fragmentation to a soft, hadronic, scale in the proton fragmentation. Whereas in the hard current fragmentation region there is a certain insight from the related phenomenology of hadronization in e^+e^- phenomenology, in the proton fragmentation region the QCD fragmentation models are helpless. At DIS'98 in Brussels the H1 [7] and ZEUS [8] collaborations reported the new experimental data which show clearly that all the popular QCD Monte-Carlo

[1] One must distinguish such **predictions** from the **parametrizations** of the parton densities by the MRS, CTEQ, GRV .... groups; the former are well defined consequences from the dynamical model whereas the latter are mere parametrizations void of any physics.

hadronization models (HERWIG, ARIADNE, LEPTO,....) fail to describe the leading baryon production.

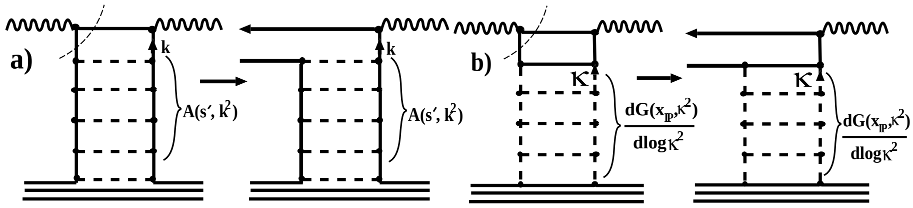

Fig. 1. a) QCD $q\bar{q}$ exchange tower (Reggeon) for DIS off valence quarks and exchange by the same $q\bar{q}$ tower in the production process. (b) QCD two-gluon (Pomeron) exchange for DIS off the sea quark and exchange by the same Pomeron in the production process

The crucial point is that at high energies and/or small x, the current fragmentation and the target fragmentation regions are separated by large rapidity and many chains of splitting of partons in the DGLAP evolution, see Fig. 1. For these reasons, quite irrespective of the specific hadronization models, the target fragmentation in general, and especially the yields of leading nucleons must not change from hadronic collisions to real photoproduction to DIS. This is one of manifestations of the so-called limiting fragmentation. Although aforementioned Monte Carlo codes have never been meant to be applicable in this soft, nonperturbative domain of the phase space, the lack of the limiting fragmentation property is surprising and shows they are based on an entirely inadequate soft input.

3. The pion, Reggeon and Pomeron exchanges

In the target fragmentation region a closer look at a correlation of the sea quarks onto mesonic clusters is in order. DIS off a pion leaves the nucleon (Δ resonance of the $\pi\Delta$ Fock state) as a spectator which emerges in the final state as a leading nucleon (Fig. 2). This is precisely the peripheral-pion exchange mechanism at work in strong interaction physics, which has been shown to exhaust the leading neutron production for small $p_\perp^2 \lesssim 0.2-0.3$ GeV^2 and the neutron Feynman variable z ∼0.7-0.9 [6].

The corollary of the plane-wave pion exchange is the factorization relation

$$f_\pi(z,p_\perp^2) = \frac{z}{\pi}\frac{d\sigma}{dzdp^2} = \frac{g_{pn\pi}^2}{2(2\pi)^3}\frac{|t|}{(t-m_\pi^2)^2}F^2(t)\left(\frac{1}{1-z}\right)^{2\alpha_\pi(t)-1}\sigma_{\rm tot}^{a\pi}(M)\,, \tag{1}$$

were $\sigma_{\rm tot}^{a\pi}(M^2=s(1-z))$ is the projectile-pion total cross section, $\alpha_\pi(t) = \alpha'_\pi(t-m_\pi^2)$ is the pion Regge trajectory and the form factor $F(t)$ describes

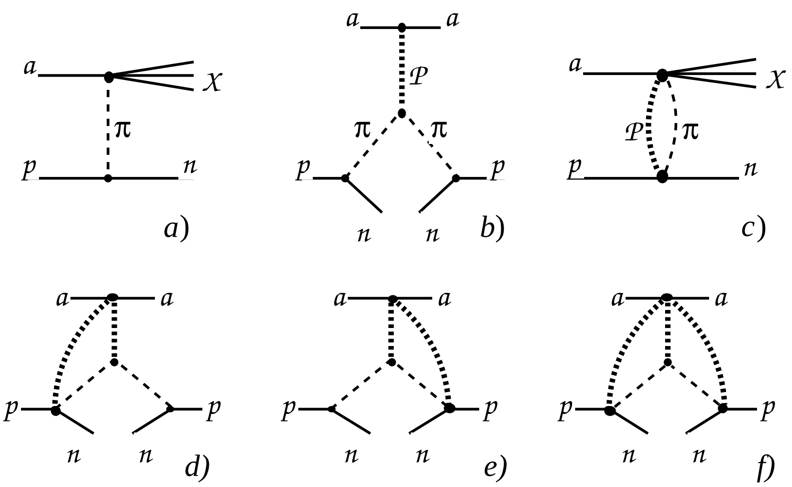

Fig. 2. (a) The plane-wave pion exchange mechanism for $ap \to Xn$ (b) the corresponding triple-Regge diagram for the inclusive cross section, (c) absorbed pion exchange, (d)–(f) absorptive corrections to the inclusive cross section.

the off-shell effects. Based on this factorization we suggested in [2] that triggering on leading neutrons one can study at HERA DIS on pions down to very small Bjorken variables $x \sim 10^{-4}$ inaccessible in the Drell–Yan experiments (Fig. 2(a), in DIS $a = \gamma^*$). The experiments are in progress at HERA with very encouraging results reported at DIS'98 in Brussels [7, 8].

Pion exchange is but one example of the correlated $q\bar{q}$ exchange. The familiar decomposition of SF's into sea and valence quark contributions $F_2(x, Q^2) = F_{\rm sea}(x, Q^2) + F_{\rm val}(x, Q^2)$ serves to identify the QCD Reggeon and Pomeron contributions: at moderately small x the standard fits give $F_{\rm val}(x, Q^2) \propto (1/x)^\gamma$ with $\gamma \sim -0.45$, which is consistent with expectations from the reggeized ρ, A_2, ω exchanges, $\gamma \approx \Delta_R = 1 - \alpha_R$, whereas the sea SF shows a low-x behavior $F_{\rm val}(x, Q^2) \propto (1/x)^{\Delta_{\bf I\!P}(Q^2)}$ with $\Delta_{\bf I\!P}(Q^2) \sim 0.1 - 0.4$. This is similar to the Regge parametrizations of hadronic total cross sections $\sigma_{\rm tot}(ab) = \sigma_{\bf I\!P}(s/s_0)^{\epsilon_{\bf I\!P}} + \sigma_R(s/s_0)^{\epsilon_R}$ with $\epsilon_R \simeq -0.5, \epsilon_{\bf I\!P} \simeq 0.1$. The QCD Reggeon(s) is thus an exchange by the $q\bar{q}$ tower in the t-channel (Fig. 1(a)), the Pomeron is a two-gluon exchange in the t-channel (Fig. 1(b)). From elastic scattering one can go to more complex processes by simply chopping off the virtual photon corner of the elastic scattering amplitude and exchange by precisely the same $q\bar{q}$ and two-gluon towers contributes also to inelastic processes $\gamma^* p \to p' X$. This is shown in Figs. 1, in which the state X is modeled by production of the $q\bar{q}$ pair, but cutting through more gluon lines one readily obtains higher order final states X [9].

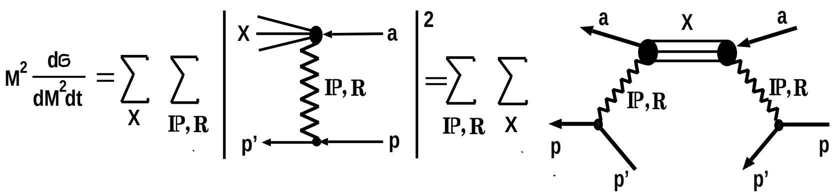

Fig. 3. Regge expansion of the inclusive cross section for $ap \to p'X$, M is the invariant mass of the inelastically excited state X.

Summing over states X one arrives at the triple-Regge like expansion of Fig. 3 for the leading proton production (I do not show explicitly the Reggeon-residue functions and signature factors):

$$\frac{d\sigma}{dzdt} = \frac{\sigma_{\rm tot}^{pp}}{16\pi(1-z)} \cdot \left[\sigma_{\rm tot}(a\mathbf{I\!P}) \cdot \left(\frac{1}{1-z}\right)^{2\epsilon_{\mathbf{I\!P}}} \right.$$
$$\left. +2\Sigma(a\mathbf{I\!P} \to aR) \cdot \left(\frac{1}{1-z}\right)^{\epsilon_{\mathbf{I\!P}}+\Delta_R} + \sigma_{\rm tot}(aR) \cdot \left(\frac{1}{1-z}\right)^{2\Delta_R}\right] . \tag{2}$$

As can be seen from the diagram in Fig. 3 there appear the forward scattering amplitudes for $a\mathbf{I\!P} \to a\mathbf{I\!P}, aR \to aR$, as well as an interference amplitude $a\mathbf{I\!P} \to aR$, which serve as a basis for the definition of the related SF's $F_{2\mathbf{I\!P},R}(\beta, Q^2) = Q^2/(4\pi^2\alpha_{em}) \cdot \sigma(\gamma^*\mathbf{I\!P}, R)$, where the relevant Bjorken variable is

$$\beta = \frac{Q^2}{Q^2+M^2} = \frac{x}{1-z} \tag{3}$$

4. An accuracy of the determination of the pion SF: absorption corrections to the limiting fragmentation

The initial state projectile-target and final state ejectile baryon-X interactions change from hadronic interaction to DIS and break the limiting fragmentation and the plane-wave Regge factorization [6]. In evaluation of absorptive triple-Reggeon diagrams of Fig. 2(d)–(f) we rely upon the extension [11] of Gribov's Reggeon calculus and of the AGK rules [12].

The scale for absorption is set by the elastic rescattering (eikonal) approximation, in which the $Pa \to Pa$ and $\pi p \to Pn$ vertices are approximated by the particle, a and n, pole contributions. The contribution of inelastic intermediate states are described by the so-called shower coefficients $C_{1,2}$ for diagrams of Fig. 2(a), (b) and (c), respectively. For $a = p$ we take the factorized form $C_1 = C_{PP}C_{P\pi}$ and $C_2 = C_{PPP}C_{P\pi}^2$, where diffraction data give $C_{PP} \approx 1.15$ [13] and $C_{PPP} \approx 1.09 C_{PP}$ as found in [14]. Our fit to the experimental data on $pp \to Xn$ [15] (see Fig. 4) and $pn \to Xp$ [16] in the region $0.7 < z < 0.9$ gave $C_{P\pi} = 0.67 \pm 0.1$ and $R^2 = -0.05 \pm 0.08$ for slope of the off-shell form factor, $F(t) = \exp[R^2(t - m_\pi^2)]$. The alternative light cone formalism as expounded in [2,17] amounts to putting $\alpha'_\pi = 0$ and the replacement $R^2 \to R^2/(1-z)$. It provides an equally viable description of the pp, pn data with parameters $R^2 = 0.19 \pm 0.07$ GeV^{-2}, $C_{P\pi} = 0.75 \pm 0.1$, so that the specific Regge effects do not play any substantial role in this kinematical domain. The found departure of the absorptive K-factor $K_{abs} = 1 + f_{abs}/f_\pi$ from unity is quite large (Fig. 5).

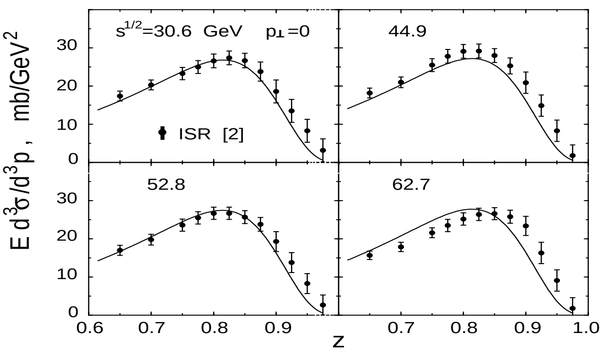

Fig. 4. Absorbed pion-exchange description [6] of the z-distribution at $p_\perp = 0$ for the $pp \to Xn$ [15].

We estimate absorption in leading neutron production in DIS in two different ways. The initial state interaction in the $\gamma^* p$ case is dominated by the well known asymmetric $q\bar{q}$ configurations in the virtual photon [19], and their rescattering can be related to the diffractive DIS cross section in precisely the same manner as in the Reggeon calculus. In the Reggeon calculus (the version DIS1) the strength of initial state rescattering is proportional to the small ratio $\xi = \sigma_D^{\gamma^* p}/\sigma_{\rm tot}^{\gamma^* p} \approx 0.07$ compared to the related parameter for $a = p$, $(\sigma_{el}^{pp} + \sigma_D^{pp})/\sigma_{\rm tot}^{pp} \approx 0.25$. However, the Reggeon calculus prescription that only the projectile is absorbed is questionable. Indeed, the final state X, created in DIS after color exchange between the hadronic $q\bar{q}$ Fock component of the virtual photon and the pion, looks like a color octet-octet system, $X_{DIS} = (q\bar{q})_8(q\bar{q})_8$. In the pp collision, similar color exchange between the proton and pion creates $X_{pp} = (qqq)_8(q\bar{q})_8$. The both color octet-octet states will have a similar transverse size, perhaps by a factor $\sim \sqrt{2}$ larger for the X_{pp} state. Consequently, the strength of the final state interaction of the state X_{DIS} with the spectator neutron will be as large as $\sim \frac{1}{2}$ of that of the state X_{pp} in the pp collision. We can model this final state interaction taking in DIS for the $C_{P\pi}$ a half of its value for the $pp \to Xn$ reaction. The results for this option DIS2 are presented in Fig. 5.

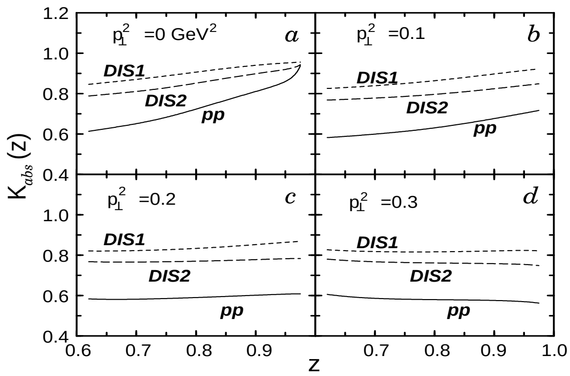

Fig. 5. The predicted absorptive K_{abs}-factor for pp scattering and two models for DIS described in the text.

From the comparison of K_{abs} for DIS1 and DID2 we conclude that the residual model dependence of absorption can be as large as ~ 20 per cent. However, one can live well with the above uncertainty because it effects neither β nor Q^2 dependence and the neutron-tagged DIS at HERA will provide a unique and reliable information on the small β pion SF, which will be not only complementary to, but competitive with, the Drell-Yan data. On the large-β end, $\beta \sim 0.1$, one can check a consistency with the Drell–Yan data.

Finally, because the small-β DGLAP evolution of the pion structure function must be very similar to the small-x evolution of the proton structure function, the pion exchange mechanism is perfectly consistent with the limiting fragmentation.

5. The leading protons

The basis of our analysis of the leading proton production is an expansion (2). Apart from the Pomeron and Reggeon exchanges one needs to include the π^0 exchange (spectator protons from the πN Fock state of the proton) and protons from decays of spectator Δ's of the $\pi\Delta$ Fock state of the proton. The contribution from diffraction excitation of protons to high mass states can be neglected [3].

The pion exchange contribution to proton production is given by formula (1) times the isospin factor $\frac{1}{2}$, for the related analysis of the Δ production see [17]. For the pion SF one can use any of the DGLAP analyses [18].

Neither Pomeron nor Reggeon can be treated as a particle [19, 20]. Still with certain reservations one can introduce the SF of the Pomeron and Reggeon and also the Pomeron–Reggeon interference SF as indicated in Fig. 6. Using an approximate DGLAP formula for the low $x_{\mathbf{IP}}$–limit $dv(x_{\mathbf{IP}},\bar{Q}^2)/d\ln Q^2 = C_F\alpha_S(Q^2)/(2\pi\alpha_R)v(x_{\mathbf{IP}},Q^2)$, one finds extremely nice result the large-β semi-inclusive SF [9], which generalizes the early results for the diffractive SF [19–21]

$$F_2^{D(3)}(x_{\mathbf{IP}},\beta,Q^2) \propto \beta(1-\beta)^2\alpha_S^2(\bar{Q}^2)\left|\eta_{\mathbf{IP}}G(x_{\mathbf{IP}},\bar{Q}^2)+\eta_R\frac{C_F}{2\pi\alpha_R}x_{\mathbf{IP}}v(x_{\mathbf{IP}},\bar{Q}^2)\right|^2,$$

where the hardness scale $\overline{Q}^2 = (m_q^2+\vec{k}_\perp^2)/(1-\beta)$. Similar analysis can be repeated also for small β.

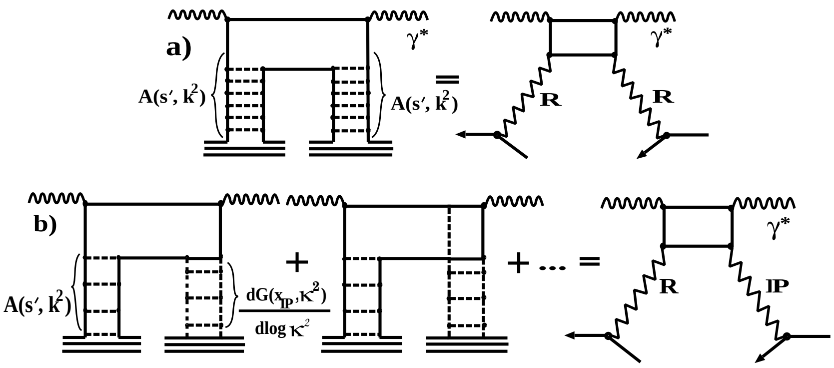

Fig. 6. Diagrams for the diffractive cross section: a) RR-contribution, b)R**IP**-interference. Not shown is the **IPIP** term that arises from squaring the amplitude in Fig. 1(b)).

The Reggeon exchange gives the manifestly leading twist semi-inclusive structure function. There is about maximal $R\mathbf{IP}$–interference. Furthermore, the large-β dependence of the Reggeon, Pomeron and Reggeon–Pomeron interference SF's is identical. Following the analysis in [19] we can argue that the small-β behavior of the Reggeon SF will be similar to that of the pion SF. Because of this DGLAP evolution of the small-β Pomeron, Reggeon and Pomeron–Reggeon interference SF's, the predicted spectrum of leading protons satisfies the limiting fragmentation. Because for the dominant contribution to the semi-inclusive SF the hardness scale $\overline{Q}^2$ is small the evaluation of this SF is somewhat model dependent and at the moment the normalization of the f-Reggeon structure function is the free parameter of the model. But our knowledge of the valence and gluon SF's implies that the result is in the correct order in magnitude with what can be expected from the analysis of the H1 data [4, 10].

A comparison with the preliminary ZEUS data [22] shows that within the ZEUS cuts about 50% of the leading protons are due to the f-exchange.

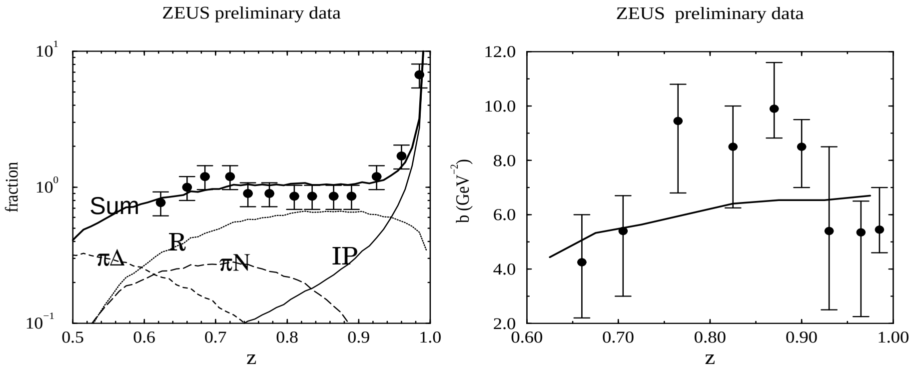

Fig. 7. The left box: the fraction (in per cent) of DIS events with a leading proton in a given z bin ($\Delta z = 0.03$) predicted by Jülich-Landau-Cracow model (thick solid curve) vs. the preliminary ZEUS data [22]. The contributions of four major mechanisms are shown separately. The right box: the slope of the t-distributions predicted by the model for $B_R = 4$ GeV^{-2} vs. the preliminary ZEUS data [22].

For the Regge model fluxes [4], this requires $F_{2R} \approx 5F_{2\mathbf{IP}}$, which is consistent with estimates of the Reggeon effect in diffractive DIS. For the slope B_R in the parametrization $G_R(t) \propto \exp(B_R t)$ we take $B_R = 4$ GeV^{-2} as suggested by production of leading protons in hadronic collisions.

Contributions of different mechanisms are shown in Fig. 7. The importance of the Reggeon exchange is obvious, it makes the z-spectrum approximately flat at $z \lesssim 0.9$, in close similarity to a flat z-spectrum of leading protons in hadronic interactions [23]. The present data are insensitive to the Pomeron–Reggeon interference, but the higher precision data would allow to test the interesting QCD predictions for the interference SF. A more detailed comparison of our predictions for both the leading neutron [2] and leading proton [5] production with the H1 data has been reported at DIS'98 by Nunnemann [7]. The agreement is good over the whole range of x, Q^2 and confirms the DGLAP evolution of semi-inclusive SF inherent to our mechanisms. Nunnemann emphasizes that other hadronization models fail to describe the observed Q^2 dependence of the leading baryon production.

The z-dependence of slope $b(z)$ of the t-distributions is shown in Fig. 2 and is controlled mostly by the Regge effects, $b_R(z) = B_R + 2\alpha'_R \log\frac{1}{1-z}$, and by the similar Regge behavior for pion exchange contribution. The increase of the slope at large z is tamed by the small diffraction slope of the Pomeron contribution. Our results are consistent with the preliminary ZEUS data [22] and are very close to the slope for leading protons in pp collisions [23].

6. Conclusions

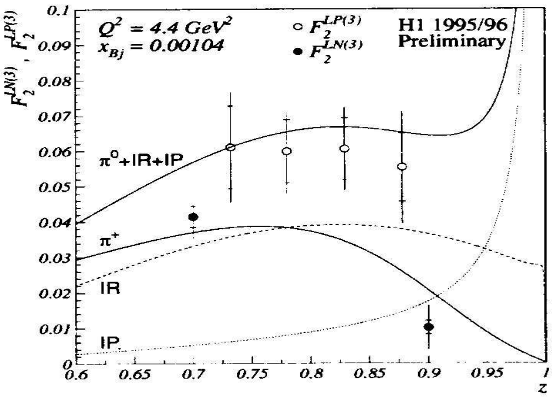

Fig. 8. The H1 data on the leading neutron (LN) and leading proton (LP) production at HERA. The theoretical curves are predictions from the Jülich-Landau-Cracow approach for leading neutrons [2] and protons [5].

The same soft mechanisms which are at work in hadronic reactions exhaust production of leading baryons in DIS in a manner consistent with the limiting fragmentation. The corollary of these soft mechanisms is the DGLAP evolution of the semi-inclusive structure functions. There are corrections to limiting fragmentation from absorption effects, but these corrections do not affect the (Q^2, x) evolution properties. In particular, they do not hinder the reliable determination of the small-x pion structure function at HERA as was proposed in [2]. The QCD considerations give a new insight into the properties of Reggeons and of the Pomeron–Reggeon interference and the forthcoming data from HERA will allow to test these QCD predictions. Incorporation of soft mechanisms of fragmentation into the hadronization Monte Carlo codes is the only way to bring them into agreement with the experiment.

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