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REPORT No. 1754/PH

REGGEON AND PION CONTRIBUTIONS IN EXCLUSIVE DIFFRACTIVE PROCESSES AT HERA

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Kraków, January 1997

PRINTED AT
THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
KRAKÓW, UL. RADZIKOWSKIEGO 152

Xerocopy: INP Kraków

Reggeon and pion contributions in exclusive diffractive processes at HERA

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Abstract

The contributions of subleading f_2, ω, a_2 and ρ reggeons to the diffractive structure function $F_2^{D(3)}(x_{\mathbf{P}}, \beta, Q^2)$ are estimated. In addition we include the pion exchange which was recently found to be responsible for the violation of the Gottfried Sum Rule. The reggeon and pion contributions lead to a violation of the factorization of the diffractive structure function. The diffractive structure function is separated into the contributions with leading proton $\Delta^{(p)}F_2^D$ and neutron $\Delta^{(n)}F_2^D$. We predict pronounced increase of the ratio $\Delta^{(n)}F_2^D/\Delta^{(p)}F_2^D$ as a function of $x_{\mathbf{P}}$ in the interval $10^{-2} < x_{\mathbf{P}} < 10^{-1}$. The effect is due to the exchange of the isovector a_2 and ρ reggeons at smaller $x_{\mathbf{P}}$ and the pion exchange at $x_{\mathbf{P}} > 10^{-2}$.

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The diffractive processes in deep inelastic scattering observed recently at the ep collider HERA at DESY by the H1 and ZEUS collaborations [1, 2], were interpreted in terms of the exchange of the leading Regge trajectory corresponding to the "soft" pomeron [3, 4, 5, 6] (for alternative explanations see [7, 8]). In this approach, first proposed by Ingelman and Schlein[9], the diffractive interaction is treated as a two-step process: an emission of the pomeron from a proton and subsequent hard scattering of a virtual photon on partons in the pomeron. The idea that the pomeron has partonic structure was experimentaly supported by the hadron collider experiments [10]. In ep scattering this idea is expressed through the factorization of the diffractive structure function

$$\frac{dF_2^D}{dx_{\boldsymbol{P}}dt}(x, Q^2, x_{\boldsymbol{P}}, t) = f^{\boldsymbol{P}}(x_{\boldsymbol{P}}, t)\, F_2^{\boldsymbol{P}}(\beta, Q^2)\,, \tag{1}$$

where $f^{\boldsymbol{P}}(x_{\boldsymbol{P}}, t)$ is the pomeron flux in the proton and $F_2^{\boldsymbol{P}}(\beta, Q^2)$ its DIS structure function. The kinematical variables are defined as follows

$$Q^2 = -q^2 \quad , \quad t = (p - p')^2 \quad , \quad x = \frac{Q^2}{2pq} \quad , \quad \beta = \frac{Q^2}{2q(p - p')} \quad , \quad x_{\boldsymbol{P}} = \frac{x}{\beta}\,. \tag{2}$$

and $q = p_e - p'_e$, where p_e, p'_e, p and p' are the momenta of the initial and final electron, initial and recoiled proton respectively.

The pomeron structure function $F_2^{\boldsymbol{P}}(\beta, Q^2)$ is related to the parton distributions in the pomeron in a full analogy to the nucleon case. Because the pomeron carries the vacuum quantum numbers, the number of independent distributions is smaller than for the proton. Recently the partonic structure was estimated [3, 4, 5], and independently fitted to the diffractive HERA data [1, 2]. Contrary to the nucleon case a large gluon component of the pomeron was found at $\beta \to 1$, [11].

New preliminary data shown by the H1 collaboration at the Eilat [12] and Warsaw [13] conferences seem to indicate breaking of the factorization (1). In order to describe this effect it was recently proposed [12, 13, 14] to include the contributions of subleading reggeons. In this generalized approach the diffractive structure function can be written as:

$$\frac{dF_2^D}{dx_{\boldsymbol{P}}dt}(x, Q^2, x_{\boldsymbol{P}}, t) = f^{\boldsymbol{P}}(x_{\boldsymbol{P}}, t)\, F_2^{\boldsymbol{P}}(\beta, Q^2) \; + \sum_R f^R(x_{\boldsymbol{P}}, t)\, F_2^R(\beta, Q^2)\,, \tag{3}$$

where f^R and F_2^R are reggeon flux and structure function respectively. [4]

In the present paper we take the pomeron flux factor of the form given in [4, 16]

$$f^{\boldsymbol{P}}(x_{\boldsymbol{P}}, t) = \frac{N}{16\pi}\, x_{\boldsymbol{P}}^{1-2\alpha_{\boldsymbol{P}}(t)}\, B_{\boldsymbol{P}}^2(t)\,, \tag{4}$$

where $\alpha_{\boldsymbol{P}}(t) = 1.08 + (0.25\ GeV^{-2})t$ is the "soft" pomeron trajectory, and $B_{\boldsymbol{P}}(t)$ describes the pomeron-proton coupling. The normalization constant is set $N = 2/\pi$, following the

[4]To be precise the term "diffractive processes" applies only to processes described by the pomeron exchange. For simplicity we shall use the same terminology for the non-pomeron reggeon exchanges including processes with the forward neutron in the final states which correspond to $I = 1$ exchange.

discussion in [16]. In analogy to the pomeron the subleading reggeon flux factors are parametrized as

$$f^R(x_{\mathbf{P}},t) = \frac{N}{16\pi}\, x_{\mathbf{P}}^{1-2\alpha_R(t)}\, B_R^2(t)\, |\eta_R(t)|^2\,, \tag{5}$$

where $\alpha_R(t) = \alpha_R(0)+\alpha_R^{'}\, t$ is the reggeon trajectory. Here $B_R(t)$ describes the coupling of the reggeon to the proton, and is assumed to have the form $B_R(t) = B_R(0)\exp\left(\frac{t}{2\Lambda_R^2}\right)$ with $\Lambda_R = 0.65\ GeV$, as known from the reggeon phenomenology in hadronic reactions [17]. The function $\eta_R(t)$ is a signature factor [18]; $|\eta_R(t)|^2 = 4\cos^2(\pi\alpha_R(t)/2)$ and $|\eta_R(t)|^2 = 4\sin^2(\pi\alpha_R(t)/2)$ for even and odd signature reggeons respectively.

The analysis done in [14] for the isoscalar reggeons (f_2,ω) shows that this contribution to the diffractive structure function becomes important for $x_{\mathbf{P}} > 0.01$. In the present paper we extend this analysis by including the isovector subleading reggeons (a_2,ρ). Although the isovector reggeons contribution to the total diffractive structure function is rather small, it becomes important for the "diffractive" processes with leading neutron in the final state. In addition, we add to our analysis one-pion exchange contribution which is expected to be important at large $x_{\mathbf{P}}$. The pionic contribution to deep inelastic lepton-proton scattering (Sullivan process) was found to provide a parameter-free description of the experimentally observed $\bar{u}-\bar{d}$ asymmetry in the proton [19].

The contributions of the mentioned above four reggeons to the diffractive structure function are estimated from the known energy dependence of the total pp, $\bar{p}p$, pn and $\bar{p}n$ cross sections (see for instance [20]). In order to find these contributions we decompose total cross sections as:

$$\begin{aligned}
\sigma_{tot}^{\bar{p}p}(s) &= \sigma_{\mathbf{P}}(s) + \sigma_{f_2}(s) + \sigma_{\omega}(s) + \sigma_{a_2}(s) + \sigma_{\rho}(s)\,, &(6)\\
\sigma_{tot}^{pp}(s) &= \sigma_{\mathbf{P}}(s) + \sigma_{f_2}(s) - \sigma_{\omega}(s) + \sigma_{a_2}(s) - \sigma_{\rho}(s)\,, &(7)\\
\sigma_{tot}^{\bar{p}n}(s) &= \sigma_{\mathbf{P}}(s) + \sigma_{f_2}(s) + \sigma_{\omega}(s) - \sigma_{a_2}(s) - \sigma_{\rho}(s)\,, &(8)\\
\sigma_{tot}^{pn}(s) &= \sigma_{\mathbf{P}}(s) + \sigma_{f_2}(s) - \sigma_{\omega}(s) + \sigma_{a_2}(s) - \sigma_{\rho}(s)\,. &(9)
\end{aligned}$$

Inverting this set of equations we find

$$\begin{aligned}
\sigma_{f_2}(s) &= \frac{1}{4}\,[\,\sigma_R^{\bar{p}p}(s) + \sigma_R^{pp}(s) + \sigma_R^{\bar{p}n}(s) + \sigma_R^{pn}(s)\,]\,, &(10)\\
\sigma_{\omega}(s) &= \frac{1}{4}[\,\sigma_R^{\bar{p}p}(s) - \sigma_R^{pp}(s) + \sigma_R^{\bar{p}n}(s) - \sigma_R^{pn}(s)\,]\,, &(11)\\
\sigma_{a_2}(s) &= \frac{1}{4}[\,\sigma_R^{\bar{p}p}(s) + \sigma_R^{pp}(s) - \sigma_R^{\bar{p}n}(s) - \sigma_R^{pn}(s)\,]\,, &(12)\\
\sigma_{\rho}(s) &= \frac{1}{4}[\,\sigma_R^{\bar{p}p}(s) - \sigma_R^{pp}(s) - \sigma_R^{\bar{p}n}(s) + \sigma_R^{pn}(s)\,]\,. &(13)
\end{aligned}$$

Inspired by the success of a recent parametrization of the total hadronic cross sections by Donnachie and Landshoff [21] we take universal form of the energy dependence:

$$\sigma_R(s) = \sigma_R(s_0)\left(\frac{s}{s_0}\right)^{-0.4525} \tag{14}$$

for each reggeon.

Now the reggeon intercept $\alpha_R(0)$ and the normalization $B_R(0)$ can be obtained from the following relation

$$\left(\frac{s}{s_0}\right)^{\alpha_R(0)-1} B_R(0) = \sigma_R(s) = \sigma_R(s_0)\left(\frac{s}{s_0}\right)^{-0.4525} \quad (15)$$

Assuming the same intercept for each reggeon, we find: $\alpha_R(0) = 0.5475$, $B^2_{f_2}(0) = 75.49$ mb, $B^2_\omega(0) = 20.06$ mb, $B^2_{a_2}(0) = 1.75$ mb and $B^2_\rho(0) = 1.09$ mb. One clearly sees the following ordering

$$B^2_{f_2}(0) > B^2_\omega(0) \gg B^2_{a_2}(0) \sim B^2_\rho(0)\ , \quad (16)$$

which implies dominance of isoscalar reggeons over isovector ones. One should remember, however, that the contributions of the latter will be enhanced by the appropriate isospin Clebsch-Gordan factor of 3, when going to deep-inelastic ep scattering and including both forward proton and neutron in the final state.

In Fig.1 we show the f_2, ω, a_2^0 and ρ^0 reggeon flux factors as a function of $x_{\boldsymbol{P}}$ integrated over t up to the kinematical limit $t_{max}(x_{\boldsymbol{P}}) = -\frac{m_N^2 x_{\boldsymbol{P}}^2}{1-x_{\boldsymbol{P}}}$. In general the flux factors reflect the ordering of the normalization constants (16). A small difference in shapes at large values of $x_{\boldsymbol{P}}$ is caused by the fact that the signature factors are different for the positive and negative signature reggeons. A more complicated structure at larger $x_{\boldsymbol{P}} > 0.1$ (not shown in Fig.1) comes from the integration limits $t_{max}(x_{\boldsymbol{P}})$. One should remember, however, that the Regge (high-energy) approximation applies exclusively to small $x_{\boldsymbol{P}}$ values, definitively smaller than 0.1. The extension of the Regge parametrization to larger $x_{\boldsymbol{P}}$, as done for instance in [23], seems questionable and would lead to unphysically large isoscalar reggeon contributions to the nucleon deep inelastic structure function. For comparison we also present in Fig.1 the pomeron (solid line) and pion (dashed line) flux factors.

The pion flux factor $f(x_\pi, t)$ has the following form resulting from the one pion exchange model

$$f_{\pi N}(x_\pi, t) = \frac{g^2_{p\pi^0 p}}{16\pi^2} x_\pi \frac{(-t)|F_{\pi N}(x_\pi, t)|^2}{(t - m_\pi^2)^2}\ , \quad (17)$$

where $g_{p\pi^0 p}$ is the pion-nucleon coupling constant and $F_{\pi N}(x_\pi, t)$ is the vertex form factor which accounts for extended nature of hadrons involved. The variable x_π is a fraction of the proton longitudinal momentum carried by the pion, equal to $x_{\boldsymbol{P}}$ defined in (2). The form factors used in meson exchange models are usually taken to be a function of t only. This assumption corresponds to setting the pion Regge trajectory $\alpha_\pi(t) = 0$. Here for simplicity we shall use the same exponential form factor as for the reggeon-nucleon coupling in formula (5). The cut-off parameter $\Lambda_\pi = 0.65\ GeV$ gives the same probability of the $\pi N'$ component as that found in [19]. As seen from the figure the pionic contribution becomes important only at $x_{\boldsymbol{P}} > 0.05$. It was shown recently, however, that this component gives rather small contribution to large rapidity gap events [24]. Already a brief comparison of the reggeon and pomeron flux factors suggests increasing role of reggeons with increasing $x_{\boldsymbol{P}}$. We shall consider this problem in more detail below.

The calculation of the diffractive structure function (3) requires knowledge of parton distributions in the pomeron and reggeons in addition to the flux factors. The quark distributions in the pomeron cannot be at present derived from first principles, but can be estimated using Regge phenomenology, based on results from hadronic diffractive reactions [3, 4, 5]. They can also be constrained by the recent diffractive HERA data.

The structure function of the reggeon is in principle also unknown. It can be, however, estimated in the small β region using the method based on the triple Regge limit of the diffractive scattering [4, 14, 15]. The method leads to the same dependence of the reggeon structure function on β (for small β) as for the pomeron one

$$F_2^R(\beta) = A_R\, \beta^{-0.08}\ . \tag{18}$$

The coefficents $A_{I\!P}$ for the pomeron and A_R for the reggeon are related to the triple Regge $I\!P I\!P I\!P$ and $RRI\!P$ couplings respectively. The ratio of these coefficients

$$C_{enh} = \frac{A_R}{A_{I\!P}}\ , \tag{19}$$

is varied in the interval $1 < C_{enh} < 10$, as suggested by the triple Regge analysis of the diffractive processes in hadronic reactions [14]. We extrapolate the parametrization of F_2^R to the region of moderate and large values of β by multiplying the r.h.s. of formula (18) by $(1-\beta)$.

In contrast to the pomeron and reggeon cases the structure function of the pion at large β is fairly well known. On the contrary the region of small β cannot be constrained by the available experimental data. In our calculations we shall take the pion structure function as parametrized in [25], which in the region of $\beta > 0.1$ properly describes the pion-nucleus Drell-Yan data.

Having fixed all ingredients we shall calculate the contributions of different reggeons to diffractive structure function $F_2^{D(3)}(x, Q^2, x_{I\!P})$, where t was integrated out. Our main aim is to demonstrate the possible effect of factorization breaking due to the subleading Regge trajectories.

In Fig.2 we show $x_{I\!P} F_2^{D(3)}$ as a function of $x_{I\!P}$ at $Q^2 = 4$ GeV^2, for two extreme values of $\beta = 0.01$ and 0.7 and two values of $C_{enh} = 2$ and 10, calculated with quark distribution functions in the pomeron from [4]. We expect that a future HERA data will allow to fix the presently unknown parameter C_{enh}. The evident rise of the $F_2^{D(3)}$ structure function at $x_{I\!P} > 0.02$ is an effect of the subleading reggeons and pions; the reggeons contribution being considerably bigger for $C_{enh} = 10$ and almost identical to the pion contribution for $C_{enh} = 2$ (compare dashed and dash-dotted lines). It should be noted that the rise of the structure function is not far from the region where the Regge parametrization is not expected to be valid, therefore some caution is required in the analysis of the experimental data.

The model presented above allows to separate the diffractive structure function into two distinct contributions

$$F_2^{(D,3)}(\beta, x_{I\!P}, Q^2) = \Delta^{(p)} F_2^{D(3)}(\beta, x_{I\!P}, Q^2) + \Delta^{(n)} F_2^{D(3)}(\beta, x_{I\!P}, Q^2)\ , \tag{20}$$

where the upper indices p and n denote the leading proton or neutron observed in the final state respectively. To calculate the functions $\Delta^{(p)}F_2^{D(3)}$ and $\Delta^{(n)}F_2^{D(3)}$ we make use of the isospin symmetry for the flux factors of the corresponding reggeons:

$$f_{\rho^+}(x_{\mathbf{P}}) = 2\ f_{\rho^0}(x_{\mathbf{P}}) \qquad \text{and} \qquad f_{a_2^+}(x_{\mathbf{P}}) = 2\ f_{a_2^0}(x_{\mathbf{P}})\ . \tag{21}$$

The recent discovery of large rapidity gap events is based on the inclusive analysis of rapidity spectra of particles which entered the main calorimeter. It is expected that these events are associated with the production of a fast baryon, the proton being probably the dominant case. Up to now these fast particles could not be observed at HERA. The installation of the leading proton spectrometer and forward neutron calorimeter opens up a possibility to analyze the diffractive events more exclusively. In particular these experimental efforts will allow to answer the question what fraction of diffractive deep inelastic events is associated with the emission of fast forward proton/neutron.

In Figs.3 and 4 we show the model ratios defined as

$$\begin{aligned} R_p^{D(3)} &= \frac{\Delta^{(p)}F_2^{D(3)}}{\Delta^{(p)}F_2^{D(3)} + \Delta^{(n)}F_2^{D(3)}}\,, \\ R_n^{D(3)} &= \frac{\Delta^{(n)}F_2^{D(3)}}{\Delta^{(p)}F_2^{D(3)} + \Delta^{(n)}F_2^{D(3)}}\,, \end{aligned} \tag{22}$$

for two values of $C_{enh} = 2$ and 10.

In the present model calculation the proton fraction $R_p^{D(3)}$, see Fig.3, is very close to unity at small $x_{\mathbf{P}}$ and deviates down to 0.8 for $x_{\mathbf{P}} = 0.1$. At small $x_{\mathbf{P}}$ the pomeron contribution (dotted line) dominates. The reggeon contribution (dashed line) becomes important only at $x_{\mathbf{P}} > 0.01$. The reggeon contribution is mainly due to isoscalar f_2 and ω exchanges. The contribution of isovector a_2 and ρ exchanges is practically negligible. The same is true for the pion contribution.

The neutron fraction $R_n^{D(3)}$ is shown in Fig.4. The forward neutron production is of course entirely dominated by the isovector exchange which in the Regge pole model is described by the exchanges of ρ and a_2 reggeons and eventually also by the pion exchange. At low $x_{\mathbf{P}}$, where the diffractive structure function is dominated by the pomeron exchange the neutron fraction $R_n^{D(3)}$ is negligible. In the region between $10^{-2} < x_{\mathbf{P}} < 10^{-1}$ the ratio increases dramatically. The rise of the neutron fraction $R_n^{D(3)}$ is caused initially ($x_{\mathbf{P}} < 10^{-2}$) by the isovector reggeons a_2 and ρ, and at $x_{\mathbf{P}} > 10^{-2}$ the pion exchange becomes the dominant mechanism.

One remark is here in order. In the present analysis we have intentionally ignored the production of neutrons emitted from the decay of the proton resonances produced by the pomeron exchange. This analysis is by far more complicated and will be presented elsewhere. We expect that the missing mechanism will dilute $R_n^{D(3)}$ by adding a new, rather flat, contribution.

To summarize, we have explored a potential of the future exclusive diffractive deep inelastic scattering which may shed new light on the physics of reggeons known up to now from hadronic reactions. In particular, we find that the exchange of isovector reggeons as well as pions leads to the increasing ratio of diffractive structure functions with leading neutron and proton $\Delta^{(n)}F_2^{D(3)}/\Delta^{(p)}F_2^{D(3)}$ as a function of $x_{\mathbf{P}}$ in the interval $10^{-2} < x_{\mathbf{P}} < 10^{-1}$. Up to now it was not possible to distinguish the two contributions in (20). This will be, however, possible in near future by using the leading proton spectrometer [26] and the forward neutron calorimeter [27], installed recently by the ZEUS and H1 collaborations. We expect that the novel effect predicted here can be verified in these experiments.

Acknowledgments

One of us (A.S.) is indebted to Lev Lipatov for an interesting discussion. This research has been supported in part by the Polish State Committee for Scientific Research grant no. 2 P03B 231 08 and 2 P03B 184 10, and by the Stiftung für Deutsch-Polnische Zusammenarbeit, project no. 1522/94/LN.

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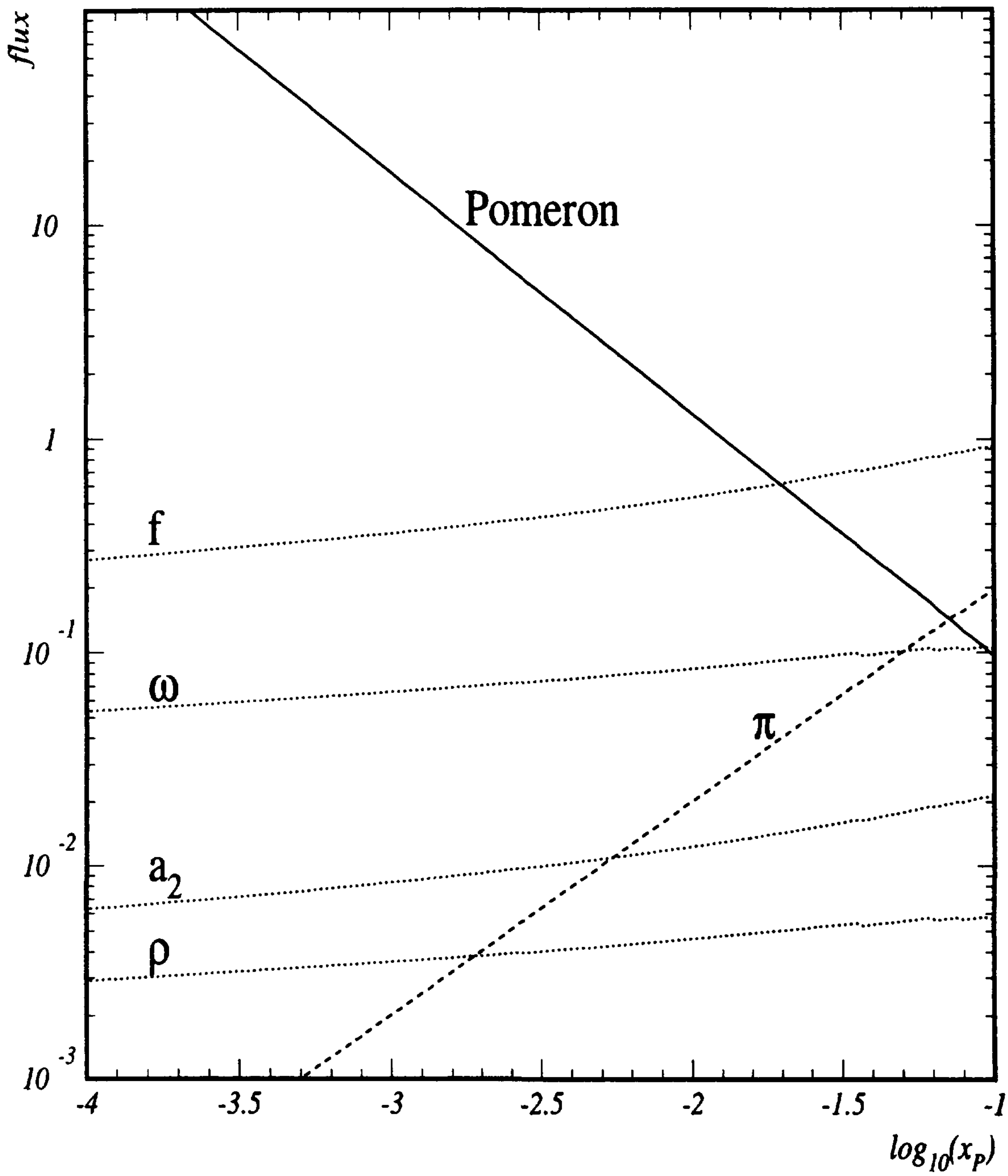

Figure 1: The integrated over t flux factors of f_2, ω, a_2 and ρ reggeons as a function of $x_{\mathbb{P}}$. For comparison we present the pomeron (dotted) and pion (solid) flux factors.

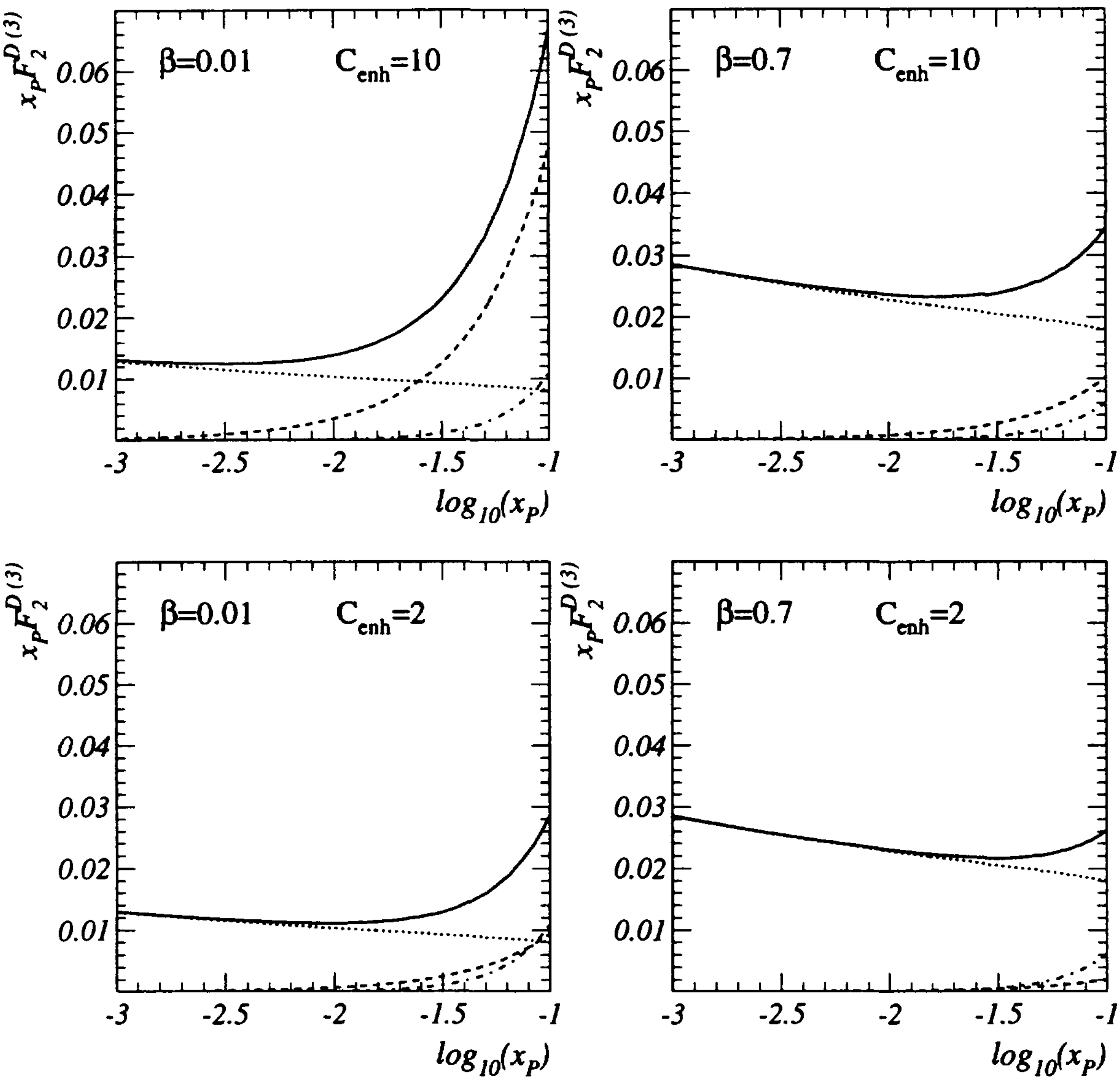

Figure 2: $x_{\mathbb{P}} F_2^{D(3)}(x_{\mathbb{P}}, \beta, Q^2)$ as a function of $x_{\mathbb{P}}$ at $Q^2 = 4$ GeV^2 for $\beta = 0.01, 0.7$ and $C_{enh} = 2, 10$. The pure pomeron contribution is marked by the dotted line, the reggeon contribution by the dashed line and the pion contribution by the dash-dotted line.

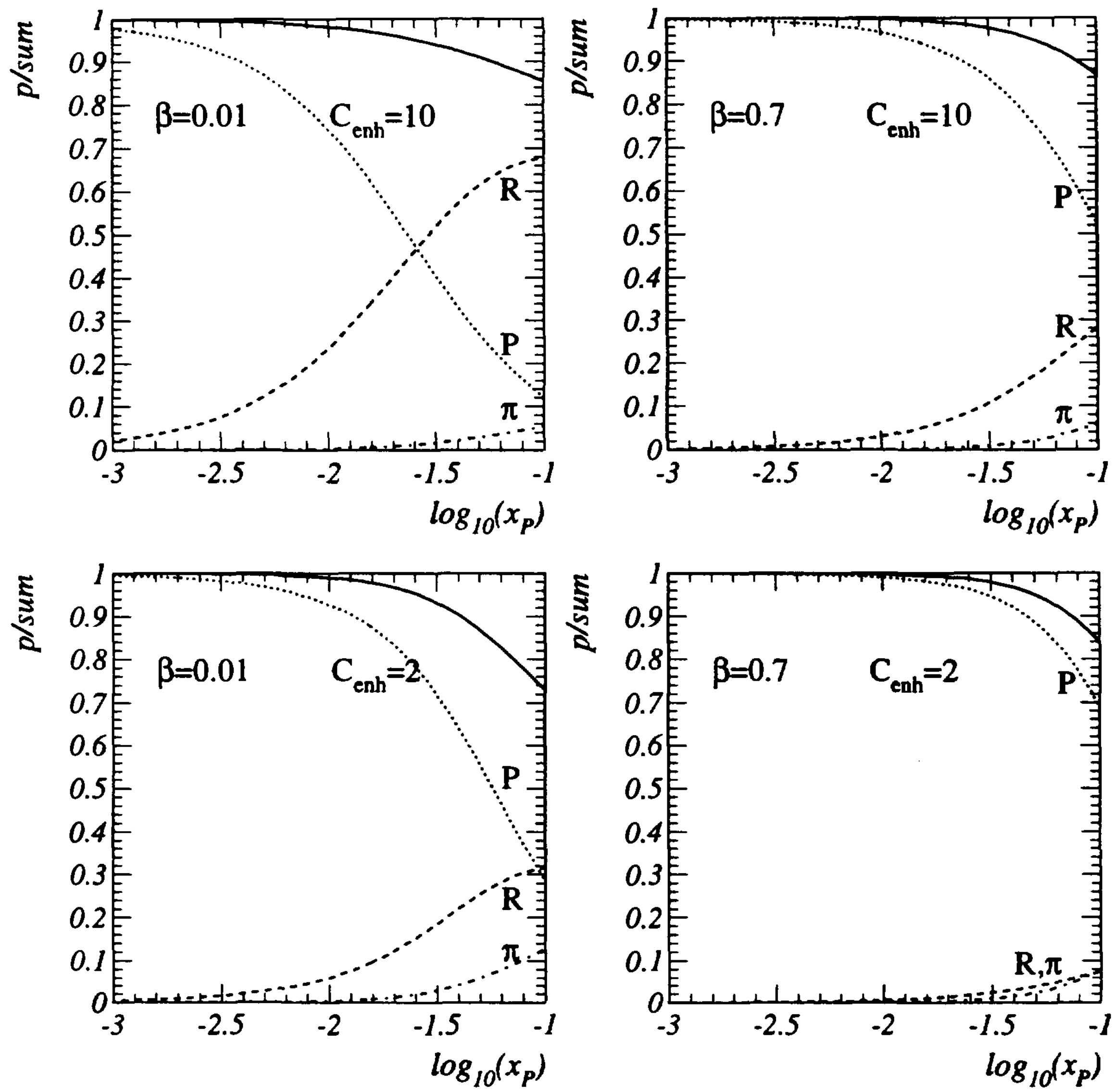

Figure 3: The proton fraction $R_p^{D(3)}$ in diffractive deep inelastic scattering as a function of $x_{\mathbb{P}}$ at $Q^2 = 4$ GeV^2 for $\beta = 0.01, 0.7$ and $C_{enh} = 2, 10$. The notation of the curves here is the same as in Fig. 2.

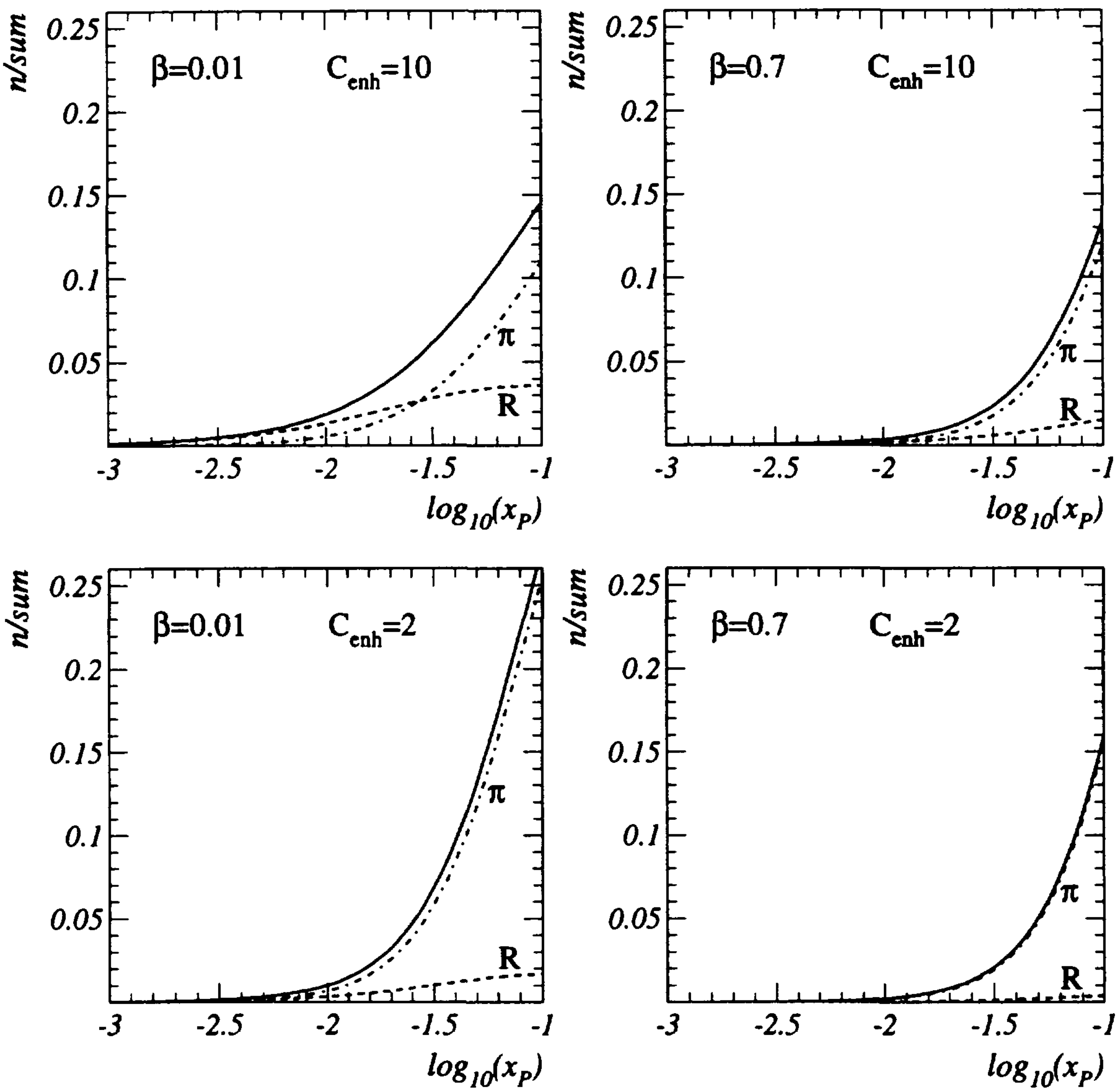

Figure 4: The neutron fraction $R_n^{D(3)}$ in diffractive deep inelastic scattering as a function of $x_{\mathbb{P}}$ at $Q^2 = 4$ GeV^2 for $\beta = 0.01, 0.7$ and $C_{enh} = 2, 10$. The notation of the curves here is the same as in Fig. 2.