A KINEMATICALLY COMPLETE DUAL-REGGE ANALYSIS OF THE PROTON STRUCTURE FUNCTION F_2 IN THE RESONANCE REGION

R. FIORE[1], A. FLACHI[2], O. IVANOVA[3,4], L.L. JENKOVSZKY[4], A. LENGYEL[5], V.K. MAGAS[4,6]

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[1]**Dipartimento di Fisica, Universita' della Calabria & INFN-Cosenza**
(I-87036 Arcavacata di Rende, Cosenza, Italy),

[2]**IFAE, Universidad Autònoma de Barcelona**
(08193 Bellaterra, Barcelona, Spain),

[3]**Physics Department, Shevchenko Kyiv National University**
(6, Ave. Academician Glushkov, Kyiv 03127, Ukraine),

[4]**Bogolyubov Institute for Theoretical Physics, Nat. Acad. Sci. of Ukraine**
(14b, Metrolohichna Str., Kyiv 03143, Ukraine),

[5]**Institute of Electron Physics**
(21, Universitetska Str., Uzhgorod 88016, Ukraine),

[6]**CFIF, Physics Department, Instituto Superior Tecnico**
(Ave. Rovisco Pais, 1049-001 Lisbon, Portugal)

A dual-Regge model of structure function F_2 is fitted to the recent data on inclusive electron-proton cross section in the resonance region ($W < 2.5$ GeV) at momentum transfers Q^2 below 4.7 (GeV$/c)^2$, measured at the JLab (CEBAF) with the CLAS detector. The new, more sophisticated parametrization for the background is proposed, what leads to significant improvement of the fit comparing to our previous results.

Introduction

Recently new data on inclusive electron-proton cross section in the resonance region ($W < 2.5$ GeV) at momentum transfers Q^2 below 4.7 (GeV$/c)^2$, measured at the JLab (CEBAF) with the CLAS detector [1] were made public. In a series of paper, a two-dimensional dual model combining Bloom—Gilman (parton-hadron) and Veneziano (resonance-Regge) duality was developed [2–4], fitting both the small-x data from HERA and the large-x from CEBAF and elsewhere in the resonance region. In the present paper, we present an analysis of the new CLAS data within this model.

The main idea behind the model is the reggeization of resonances both in the s- and t-channels. Nonlinear complex Regge trajectories replace individual resonance contributions. The resulting scattering amplitude is a complex function of the Mandelstam variables s, t, u and the photon virtuality Q^2. Its imaginary part in the forward direction, $t = 0$, corresponds to ordinary distributions or structure functions (SF) describing inclusive (e.g., electron-proton) scattering, while the whole amplitude is directly related to exclusive deeply virtual Compton scattering and corresponding general parton distributions.

The complex pattern of the nucleon structure function in the resonance region was developed long time ago (see, for example, [8]). There are several dozens of resonances in the $\gamma^* p$ system in the region above the pion-nucleon threshold, but only a few of them can be identified more or less unambiguously for various reasons. Therefore, instead of identifying each resonance, one considers a few maxima above the elastic scattering peak, corresponding to some "effective" resonance contributions. Recent results from the JLab [1,7] renewed the interest in the subject and they call for a more detailed phenomenological analysis of the data and a better understanding of the underlying dynamics. The basic idea in our approach is the use the off-mass-shell continuation of the dual amplitude with nonlinear complex Regge trajectories.

The central object of the present study is the nucleon SF, uniquely related to the photoproduction cross section by

$$F_2(x, Q^2) = \frac{Q^2(1-x)}{4\pi\alpha(1+\frac{4m^2x^2}{Q^2})}\sigma_t^{\gamma^* p}(s, Q^2) \ , \qquad (1)$$

where the total cross section, $\sigma_t^{\gamma^* p}$, is the imaginary part of the forward Compton scattering amplitude, $A(s, Q^2)$,

$$\sigma_t^{\gamma^* p}(s) = \text{Im } A(s, Q^2) \ . \qquad (2)$$

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The center-of-mass energy of the $\gamma^* p$ system, the negative squared photon virtuality Q^2, and the Bjorken variable x are related by

$$s = Q^2 \frac{(1-x)}{x} + m^2, \tag{3}$$

m is the proton mass. We adopt the two-component picture of strong interactions, according to which direct-channel resonances are dual to cross-channel Regge exchanges and the smooth background in the s-channel is dual to the Pomeron exchange in the t-channel. As explained in [2], the background corresponds in the dual model to a pole term with an exotic trajectory that does not produce any resonance.

We use Regge trajectories with a threshold singularity and nonvanishing imaginary part in the form:

$$\alpha(s) = \alpha_0 + \alpha_1 s + \alpha_2(\sqrt{s_0} - \sqrt{s_0 - s}), \tag{4}$$

where s_0 is the lightest threshold, $s_0 = (m_\pi + m_p)^2 = 1.14\ \mathrm{GeV}^2$ in our case [2–4,6].

We take the exotic trajectories in the form

$$\alpha_E(s) = \alpha_E(0) + \alpha_{1E}(\sqrt{s_E} - \sqrt{s_E - s}), \tag{5}$$

where the intercept $\alpha_E(0)$, α_{1E}, and the effective exotic threshold s_E are free parameters.

1. The Model

We present the form factors as sums of three terms [10,11]: $G_+(Q^2)$, $G_0(Q^2)$, and $G_-(Q^2)$ corresponding to $\gamma^* N \to R$ helicity transition amplitudes in the rest frame of the resonance R:

$$G_{\lambda_\gamma} = \frac{\langle R, \lambda_R = \lambda_N - \lambda_\gamma | J(0) | N, \lambda_N \rangle}{m}, \tag{6}$$

where λ_R, λ_N, and λ_γ are the resonance, nucleon, and photon helicities, $J(0)$ is the current operator; λ_γ assumes the values $-1, 0$, and $+1$. Correspondingly, the squared form factor [4] is given by the sum

$$|G_+(Q^2)|^2 + 2|G_0(Q^2)|^2 + |G_-(Q^2)|^2. \tag{7}$$

The explicit form of these form factors is known only near their thresholds $|\vec{q}| \to 0$, while their large-Q^2 behavior is constrained by the quark counting rules. In [10] the following expressions for the G's were suggested:

$$|G_\pm|^2 = |G_\pm(0)|^2 \times$$
$$\times \left(\frac{|\vec{q}|}{|\vec{q}|_{Q=0}} \frac{Q_0'^2}{Q^2 + Q_0'^2} \right)^{2J-3} \left(\frac{Q_0'^2}{Q^2 + Q_0'^2} \right)^{m_\pm} \tag{8}$$

$$|G_0|^2 = C^2 \left(\frac{Q_0^2}{Q^2 + Q_0^2} \right)^{2a} \frac{q_0^2}{|\vec{q}|^2} \times$$
$$\times \left(\frac{|\vec{q}|}{|\vec{q}|_{Q=0}} \frac{Q_0'^2}{Q^2 + Q_0'^2} \right)^{2J-1} \left(\frac{Q_0^2}{Q^2 + Q_0^2} \right)^{m_0} \tag{9}$$

for the normal transitions $(1/2^+ \to 3/2^-, 5/2^+, 7/2^-, ...)$ and

$$|G_\pm|^2 = |G_\pm(0)|^2 \times$$
$$\times \left(\frac{|\vec{q}|}{|\vec{q}|_{Q=0}} \frac{Q_0'^2}{Q^2 + Q_0'^2} \right)^{2J-1} \left(\frac{Q_0'^2}{Q^2 + Q_0'^2} \right)^{m_\pm} \tag{10}$$

$$|G_0|^2 = C^2 \left(\frac{Q_0^2}{Q^2 + Q_0^2} \right)^{2a} \times$$
$$\times \left(\frac{q_0^2}{|\vec{q}|^2} \frac{Q_0'^2}{Q^2 + Q_0'^2} \right)^{2J+1} \left(\frac{Q_0^2}{Q^2 + Q_0^2} \right)^{m_0} \tag{11}$$

for the anomalous ones $(1/2^+ \to 1/2^-, 3/2^+, 5/2^-, ...)$, where $m_+ = 3$, $m_0 = 4$, $m_- = 5$ count the quarks,

$$|\vec{q}| = \frac{\sqrt{(M^2 - m^2 - Q^2)^2 + 4M^2 Q^2}}{2M}, \tag{12}$$

$$q_0 = \frac{M^2 - m^2 - Q^2}{2M}, \tag{13}$$

M is a resonance mass. C and a are free parameters. The form factors at $Q^2 = 0$ are related to the helicity photoproduction amplitudes $A_{1/2}$ and $A_{3/2}$ by

$$|G_{+,-}(0)| = \frac{1}{\sqrt{4\pi\alpha}} \sqrt{\frac{M}{M-m}} |A_{1/2,3/2}|. \tag{14}$$

2. Comparison with Data

We have fitted the above model to the JLab data [1,7] by keeping, apart of background, only the contribution from three prominent resonances, namely $\Delta(1232)$, $N^*(1520)$ and $N^*(1680)$, i.e. we have used only three baryon trajectories with one resonance on each (for more details, see [5,6] and references therein).

As argued in [2], only a limited number of resonances appear on the trajectories, i.e. their real part is bounded. For practical reasons, we have replaced the formal condition $\mathrm{Re}\,\alpha(s) <$ const by a finite sum (actually this sum has only one term in our case), introducing a linear term in the baryon trajectory to approximate the contribution from heavy thresholds (see Eq. (4)).

For the smooth background which does not show any resonance, we keep two terms in the corresponding sum.

In the previous works, we had only one background term, but now we realize that, in order to have a good agreement, we need at least two background terms. These two terms correspond to two exotic trajectories, which contradicts neither theory nor experiment. Having different Q^2 scales Q_E^2 [5,6], see Eq. (18) below, these two terms will manifest themselves most strongly in different Q^2 regions.

For the sake of simplicity, we also neglected the cross term containing G_0 (and the coefficient C), since it is small relative to the other two terms in Eq. (7) [10].

To be specific, we write explicitly the three resonance terms, to be fitted to the data:

$$\mathrm{Im}\,A(s,Q^2) = $$

$$= \mathrm{norm}\left[\frac{f_\Delta I_\Delta}{(1-R_\Delta)^2+I_\Delta^2}+\frac{f_{N^-}I_{N^-}}{(1-R_{N^-})^2+I_{N^-}^2}+\right.$$

$$\left.+\frac{f_{N^+}I_{N^+}}{(2-R_{N^+})^2+I_{N^+}^2}+\mathrm{background}\right], \qquad (15)$$

where, e.g., f_Δ is calculated according to Eqs. (7, 8, 10):

$$f_\Delta = \left(\frac{|\vec{q}|}{|\vec{q}|_{Q=0}}\frac{Q_0'^2}{Q^2+Q_0'^2}\right)^{2J-1=2}\times$$

$$\times\left(|G_+(0)|^2\left(\frac{Q_0^2}{Q^2+Q_0^2}\right)^3+|G_-(0)|^2\left(\frac{Q_0^2}{Q^2+Q_0^2}\right)^5\right); \qquad (16)$$

R and I denote the real and imaginary parts of the relevant trajectory specified by the subscript. Similar expressions can be easily cast for f_{N^+} and for f_{N^-} as well.

The background is modeled as:

$$\mathrm{background} = \sum_{i=1}^{2}\frac{f_{Ei}I_{Ei}}{(n_{Ei}^{\min}-R_{Ei})^2+I_{Ei}^2}, \qquad (17)$$

$$f_{Ei} = G_E\left(\frac{Q_{Ei}^2}{Q^2+Q_{Ei}^2}\right)^8. \qquad (18)$$

Here, $n_{Ei}^{\min}$ is the lowest integer larger than the Max{Re α_{Ei}} (to make sure there are no resonances on the exotic trajectory). The interesting point we can learn from these fits is about the background parametrization. It seems that the background might have a smaller effect than we thought before — in the fits present in [6], the power of $\left(\frac{Q_{Ei}^2}{Q^2+Q_{Ei}^2}\right)$ in f_{Ei} (Eq. (18)) was fixed to 4. In this new fit, it tends to twice as much higher value, what makes the resonance contribution smaller.

Review of Particle Physics [9] quotes above two dozen (almost) certain resonances. Most, if not all of these — among them the three "prominent" ones mentioned in Introduction — contribute with different weights to the $\gamma^* N$ total cross section or to the nucleon SF. It is clear that a systematic account for all these resonances (plus those to be confirmed) is not an easy task. A much more economical way is to use Regge trajectories which will automatically account for all the resonances lying on the corresponding trajectory (although in the present simplified model, there is only one resonance on each trajectory). As well as generalizing the concept of a resonance, the trajectory may also be used to classify the resonances by eliminating some candidates and predicting others.

The parameters of the fit

N_1^*	α_0	–0.8377 (fixed)$^\diamond$
	α_1	0.9805
	α_2	0.1005
	$A(1/2)[\mathrm{GeV}^{-1/2}]$	0.02622
	$A(3/2)[\mathrm{GeV}^{-1/2}]$	0.1327
N_2^*	α_0	–0.37(fixed)$^\diamond$
	α_1	0.9530
	α_2	0.1147
	$A(1/2)[\mathrm{GeV}^{-1/2}]$	0.1974
	$A(5/2)[\mathrm{GeV}^{-1/2}]$	0.0025
Δ	α_0	0.0038 (fixed)$^\diamond$
	α_1	0.8655
	α_2	0.1944
	$A(1/2)[\mathrm{GeV}^{-1/2}]$	0.07068
	$A(3/2)[\mathrm{GeV}^{-1/2}]$	0.3659
	$s_0 = s_{E1} = s_{E2}$, GeV^2	1.14 (fixed)$^\diamond$
EI	α_0	1.668
	α_2	0.08969
	G_E	1.175
	Q_E^2, GeV^2	10.08
EII	α_0	0.000
	α_2	1.246
	G_E	–0.1511
	Q_E^2, GeV^2	6.452
	Q_0^2	3.021
	$Q_0'^2$	0.3384
	norm	0.05338
	$\chi^2_{d.o.f.}$	2.00

N o t e. $^\diamond$ Using intercepts and thresholds as free parameters does not improve the fit, but intercepts may get values far from original ones.

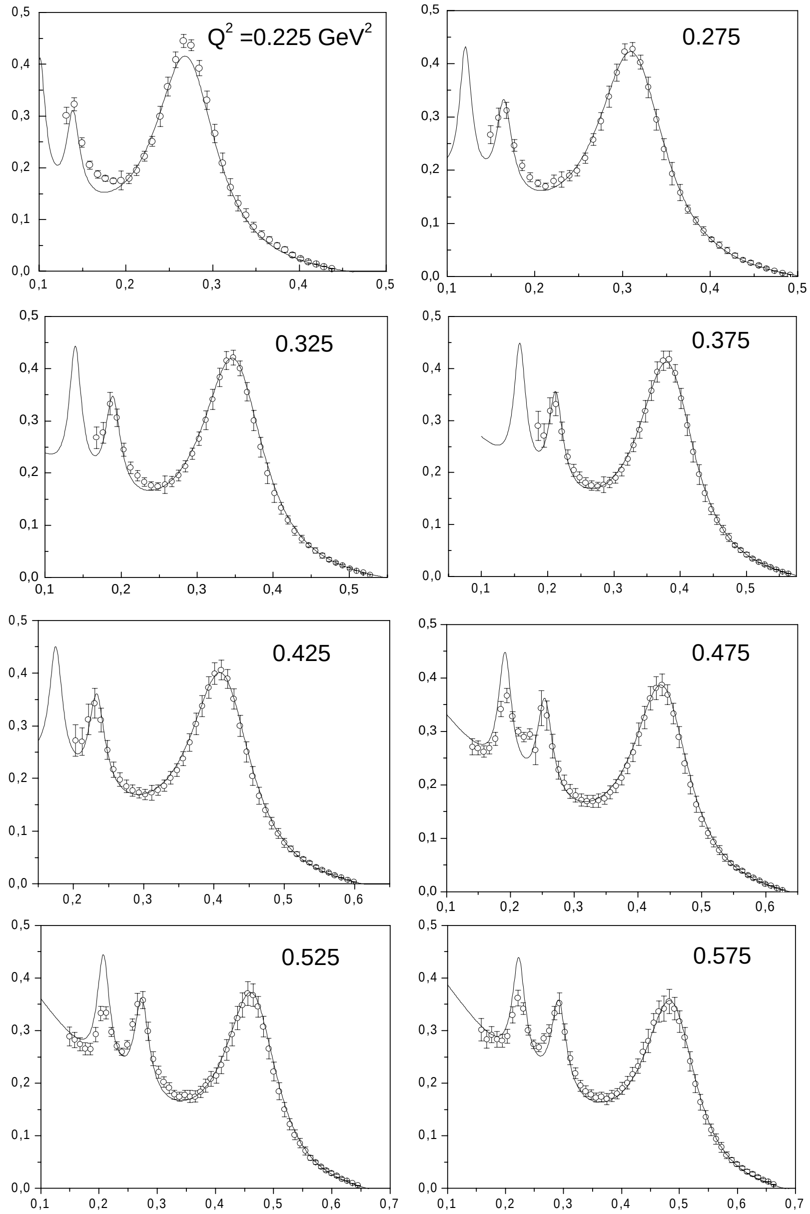

Fig. 1. Results of the fitting: F_2 as a function of x. The number in the upper right corner corresponds to value of Q^2 in GeV^2

For this reason, we consider the dominant resonances (N_1^*, N_2^* and Δ) as "effective" contributions to the SF. In other words, we require that they mimic the contribution of the dominant resonances plus the large number of subleading contributions which, together, fully describe the real physical system. In this way we use the parameters of the baryonic trajectories and the helicity photoproduction amplitudes of the corresponding resonances as free parameters (although we have to restrict the range of variation to keep these parameters more or less close to their "original" values).

The resulting fit to the CLAS data is presented in Table. Figs. 1,2 show some examples of the fit for $Q^2 = 0.225 \div 0.575$ and $4.225 \div 4.575$ GeV^2. The fit is good ($\chi^2_{\mathrm{d.o.f.}} = 2.00$), but we would like to stress that this is actually only the first fit over the new data set with a rather sophisticated two-term background. The improvement in comparison with a similar fit performed with a one-term background [5] ($\chi^2_{\mathrm{d.o.f.}} = 9.4$) is really

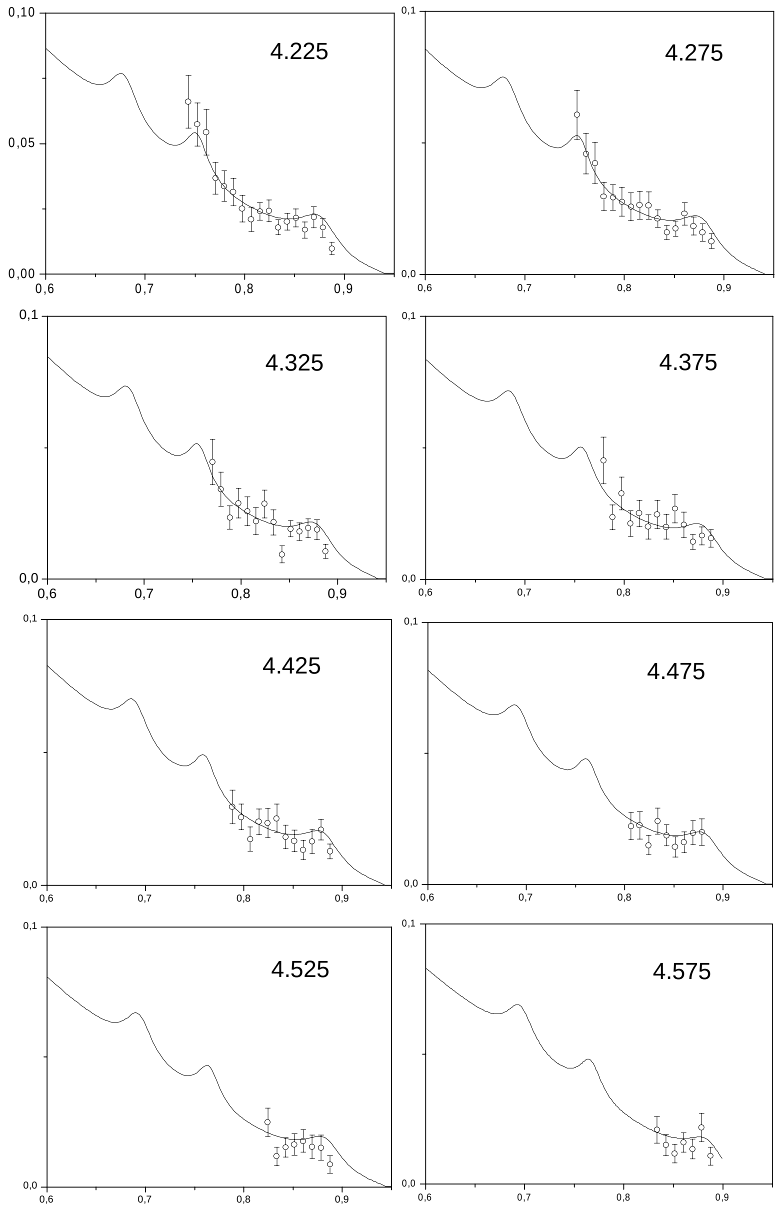

Fig. 2. Same as in Fig.1

significant (notice that the direct comparison might be a bit misleading since, in [5], a bigger data set from [1, 7] was fitted and helicity amplitudes were kept constant).

Conclusions

In this paper, we have concentrated on best fits to the new data from CLAS Collaboration [1]. As a result, we managed to improve considerably the quality of the fits with respect for the earlier paper on this subject [5].

We started from the idea that deep inelastic scattering can be described by a sum of direct channel resonances lying on Regge trajectories. The form of these trajectories, constrained by analyticity, unitarity, and experimental data is crucial for the dynamics. The use of baryon trajectories instead of individual resonances makes the model economical. On the other hand, in order to make a good fit, we had to treat our trajectories as effective ones, i.e. to let the parameters of the trajectories and the photoproduction amplitudes of corresponding resonances vary as free parameters. It is worthwhile to note that the data require different values of the parameters, than the "theoretical" (or coming from another source) ones. Hence we conclude that the construction of the model is still not complete. To this end, the following points should be clarified:

1. Realistic models for baryonic trajectories should be constructed.
2. The nature of the direct-channel background should be better understood and a further work on relevant models should be done.
3. More comparative analysis involving standard models based on classical Breit-Wigner resonance poles and the present "reggeized" approach should be carried out.

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КІНЕМАТИЧНО ПОВНИЙ АНАЛІЗ СТРУКТУРНОЇ ФУНКЦІЇ ПРОТОНА F_2 В РЕЗОНАНСНІЙ ОБЛАСТІ В ДУАЛЬНІЙ РЕДЖЕ-МОДЕЛІ

Р. Фіоре, А. Флакі, О. Іванова, Л. Єнковський, О. Лендел, В. Магас

Р е з ю м е

Дуальна редже-модель для структурної функції F_2 узгоджується з сучасними даними з інклюзивного електрон-протонного перерізу в резонансній області ($W < 2,5$ ГеВ) при переданих імпульсах Q^2, менших ніж $4,7$ (ГеВ/c)^2, який вимірювався детектором CLAS в J-Лабораторії (CEBAF). Запропоновано нову, більш складну параметризацію, для фону, що дозволило суттєвого поліпшити опис даних порівняно з нашими попередніми результатами.

КИНЕМАТИЧЕСКИ ПОЛНЫЙ АНАЛИЗ СТРУКТУРНОЙ ФУНКЦИИ ПРОТОНА F_2 В РЕЗОНАНСНОЙ ОБЛАСТИ В ДУАЛЬНОЙ РЕДЖЕ-МОДЕЛИ

Р. Фиоре, А. Флаки, О. Иванова, Л. Енковский, А. Лендел, В. Магас

Р е з ю м е

Дуальная редже-модель для структурной функции F_2 согласовывается с недавними данными по инклюзивному электрон-протонному сечению в резонансной области ($W < 2,5$ ГэВ) при переданных импульсах Q^2 меньше $4,7$ (Гэв/c)^2, измеренному детектором CLAS в J-Лаборатории (CEBAF). Предложена новая, более сложная параметризация, для фона, что приводит к существенному улучшению описания данных по сравнению с нашими предыдущими результатами.