Possible evidence of extended objects inside the proton

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Abstract

Recent data on the Nachtmann moments of the unpolarized proton structure function $F_2^p$, obtained at low momentum transfer with the CLAS detector at Jefferson Lab, are interpreted in terms of the dominance of the elastic coupling of the virtual photon with extended substructures inside the proton. The CLAS data exhibit a new type of scaling behavior and the resulting scaling function can be interpreted as a constituent form factor consistent with the elastic nucleon data. A constituent size of $\approx 0.2 \div 0.3$ fm is obtained.

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The inclusive electron-proton cross section has been recently measured in Hall B at Jefferson Lab using the CLAS spectrometer. The measurements have been performed in the nucleon resonance regions ($W < 2.5 \text{ GeV}$) for values of the squared four-momentum transfer $Q^2$ below $\approx 4.5 \text{ (GeV/c)}^2$. One of the most relevant features of such measurements is that the CLAS large acceptance has allowed to determine the cross section in a wide two-dimensional range of values of $Q^2$ and $x = Q^2/2M\nu$. This has made it possible to extract the proton structure function $F_p^p(x, Q^2)$ and to directly integrate all the existing world data at fixed $Q^2$ over the whole significant $x$-range for the determination of the (inelastic) transverse Nachtmann moments $M_n^{(T)}(Q^2)$ with order $n = 2, 4, 6, 8$, defined as

$$M_n^{(T)}(Q^2) \equiv \int_0^{x_\pi} dx \frac{\xi^{n+1}}{x^3} \frac{3 + 3(n + 1)x + n(n + 2)x^2}{(n + 2)(n + 3)} F_p^p(x, Q^2) ,$$

where $\xi = 2x/(1 + r)$, $r = \sqrt{1 + 4M^2x^2/Q^2}$ and $x_\pi$ is the pion threshold.

A possible interpretation of the experimental results of Ref. has been proposed in Ref. There the original two-stage model of Ref. developed in the Deep Inelastic Scattering (DIS) regime, is extended to values of $Q^2$ around and below the scale of chiral symmetry breaking, $\Lambda_\chi$, and above the QCD confinement scale, $\Lambda_{QCD}$, i.e. $0.1 \div 0.2 \lesssim Q^2 \text{ (GeV/c)}^2 \lesssim 1 \div 2$. In this contribution we briefly recall the main results of Ref. , namely: i) the data of Ref. exhibit a new type of scaling behavior expected within the generalized two-stage model, and ii) the resulting scaling function can be interpreted as (the square of) a constituent quark ($CQ$) form factor with a $CQ$ size of $\approx 0.2 \div 0.3 \text{ fm}$.

The basic assumption of the two-stage model is that hadrons are made of a finite number of $CQ$’s having a partonic structure. The latter depends only on short-distance physics, independent of the particular hadron, while the motion of the $CQ$’s inside the hadron reflects non-perturbative physics depending on the particular hadron. For values of $Q^2$ around and below the scale of chiral symmetry breaking, one expects that the elastic coupling of the incoming virtual boson with the $CQ$ dominates over the inelastic channels. As explained in Ref. , the $Q^2$-range of applicability of the generalized two-stage model is qualitatively given by $\Lambda_{QCD}^2 \lesssim Q^2 \lesssim \Lambda_\chi^2$, i.e. $0.1 \div 0.2 \lesssim Q^2 \text{ (GeV/c)}^2 \lesssim 1 \div 2$.

The dominance of the elastic coupling at the $CQ$ level cannot however hold at each $x$ value, but only in a local duality sense. The $CQ$-hadron duality can be translated in the space of moments into the following (approximate) equivalence

$$M_n^{(T)}(Q^2) \approx F_p(Q^2) \cdot \overline{M}_n^{(T)}(Q^2) ,$$

where $\overline{M}_n^{(T)}(Q^2)$ describes the effect of the internal $CQ$ motion inside the hadron on the moment of order $n$, and $F_p(Q^2)$ is the $CQ$ elastic form factor (see Ref. for its definition). Equation is expected to hold for low values of the order $n$, except $n = 2$, because the second moment $M_2^{(T)}(Q^2)$ is significantly affected by the low-$x$ region where the concept of valence dominance may become unreliable (cf. for more details Ref.).

If one has a reasonable model for the $CQ$ momentum distributions in the hadron, the
theoretical moments $\overline{M}_n^{(T)}(Q^2)$ can be estimated and therefore the ratio

$$R_n^{(T)}(Q^2) \equiv \frac{M_n^{(T)}(Q^2)}{\overline{M}_n^{(T)}(Q^2)}$$

(3)

can be constructed starting from the experimental moments $M_n^{(T)}(Q^2)$. Thus, if Eq. (2) holds, the ratio $R_n^{(T)}(Q^2)$ is expected to depend only on $Q^2$, i.e. it becomes independent of the order $n$ (as well as on the specific hadron), viz.

$$R_n^{(T)}(Q^2) \simeq F^2(Q^2).$$

(4)

The scaling function, given by the r.h.s. of Eq. (4), is directly the square of the $CQ$ form factor, i.e. the form factor of a confined object.

The data of Ref. [1] manifest a clear tendency to the scaling property (4) even assuming no internal $CQ$ motion inside the proton, which represents a very simplified and rough model for the $CQ$ momentum distribution. Explicitly one gets $\overline{M}_n^{(T)}(Q^2) \rightarrow (1/3)^{n-1}$. Though simple, such an hypothesis explains very well the spread of about one order of magnitude between the experimental moments of order $n$ and $(n+2)$ (cf. Ref. [2]). In our opinion this is an important result (almost a pure experimental result) because obtained with a very simple hypothesis about the $CQ$ motion in the proton.

The effect of the internal $CQ$ motion was investigated in Ref. [2] and found to be important. The basic result of Ref. [2] is represented in Fig. 1, where it can clearly be seen that the scaling property (4) is well satisfied by the CLAS data for $n = 4, 6, 8$ with the expected exception of $n = 2$. The scaling function of Fig. 1 can be interpolated using the square of a monopole ansatz, $F(Q^2) \simeq 1/(1 + r_Q^2 Q^2/6)$, with $r_Q = 0.21 \text{ fm}$. The precise value of the $CQ$ size $r_Q$ depends on the specific values of the model parameters. Such a dependence has been thoroughly investigated in Ref. [2] and the final result is that a safe estimate of the $CQ$ size $r_Q$ is between $\approx 0.2$ and $\approx 0.3 \text{ fm}$.

The $CQ$ form factor extracted from the scaling function and the model used for the nucleon elastic wave function should be consistent with the elastic nucleon data. In Ref. [2] the nucleon elastic form factors were calculated adopting the covariant light-front approach of Ref. [1], which is properly formulated at $q^+ = 0$. It turns out that the calculated nucleon form factors slightly overestimate the data, but a nice consistency can be easily reached through small variations of the model parameters.

In conclusion the generalized two-stage model of Ref. [2] provides an explanation of the recent CLAS data of Ref. [1] in terms of the dominance of the elastic coupling of the virtual photon with extended objects inside the proton at low values of $Q^2$, namely $0.1 \div 0.2 \lesssim Q^2 (GeV/c)^2 \lesssim 1 \div 2$. A positive comparison with forthcoming data on other structure functions, like the longitudinal (see Ref. [3]) and the polarized ones, will provide further compelling evidence that constituent quarks are intermediate substructures between the hadrons and the current quarks and gluons of QCD.
Figure 1: Ratio $R_n^{(T)}(Q^2)$ of the experimental moments $M_n^{(T)}(Q^2)$, obtained in Ref. [1], with the theoretical moments $\overline{M}_n^{(T)}(Q^2)$, calculated in Ref. [2]. The dotted line represents the square of a monopole form factor corresponding to a $CQ$ size $r_Q = 0.21$ fm. The dots, squares, diamonds and triangles correspond to $n = 2, 4, 6$ and 8, respectively. (Adapted from Ref. [2]).

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