Partonic structure of proton in the resonance region

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Abstract

We separate the contributions of parton distributions from higher twist corrections to the deeply inelastic lepton-proton scattering in the resonance region using the Jefferson Lab data at low $Q^2$. The study indicates that the concept of the valence quarks and their distributions are indispensable even at $Q^2 < 1 \text{GeV}^2$. The quark-hadron duality is also discussed.

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The theoretical description of nucleon structure in the transition region between perturbative and non-perturbative QCD is still an open question. Structure function data in the lepton-nucleon deeply inelastic scattering (DIS) are important measurements in the investigations of the nucleon structure. Jefferson Lab (JLab) has measured the proton structure function $F_2^p$ at $0.07 \leq Q^2 \leq 3.3 GeV^2$ and $W^2 < 4 GeV^2$ [1] ($W^2$ is the invariant mass of the final hadronic state) almost two decades ago. However, we still do not have a complete understanding of this experiment.

According to standard model, proton consists of quarks and gluons, which are complicatedly correlated to each other by strong interaction. In this work we try to extract the information about the quark structure in the proton at low $Q^2$ (down to 0.07GeV$^2$) from the JLab data. According to the operator product expansion (OPE) method, the proton structure function can be decomposed as

$$F_2^p(x, Q^2) = F_2^{LT}(x, Q^2) + F_2^{HT}(x, Q^2),$$

where $F_2^{LT}(x, Q^2)$ is the leading twist contribution, and $F_2^{HT}(x, Q^2)$ is the higher twist corrections. The leading twist (LT) part of the structure function directly relates to the parton distributions, which are usually defined as the single, non-interacting partons at $Q^2 > 1 GeV^2$ and their $Q^2$-evolution is well studied by pQCD theory. However the quantity of higher twist (HT) corrections is not clear in QCD theory. Because it corresponds to multi-parton interactions and connected to the complicated nonperturbative QCD effects. It is expected that the structure functions at low $Q^2$ can provide important information of the higher twist effects since they are power $1/Q^{2n}$-dependent.

To separate the higher twist effects using the JLab data at low $Q^2$ in Ref. [1], we need to know: (a) how to measure $F_2^p(x, Q^2)$ in the resonance region? (b) how to calculate
the $F_2^{LT}(x, Q^2)$ at $Q^2 < 1 GeV^2$? For the first question, the work [1] has obtained the single curves $\overline{F}_2^p(x, Q^2)$ using the quark-hadron duality [2], which are the integrals of the resonance curves integrated in a defined $x$-range, corresponding to the resonance region. In this work we take

$$F_2^p(x, Q^2) = \overline{F}_2^p(x, Q^2),$$

in the resonance region from Ref. [1]. For the second question, unfortunately, most of the PDF global analyses are performed in the range of $Q^2 > 1 GeV^2$. There are only two global analyses which give the parton distributions at low $Q^2 < 1 GeV^2$. One of them is the Glück-Reya-Vogt (GRV) PDFs [3], where the valence quarks and valence-like gluon evolve from $\mu^2 \sim 0.3 GeV^2$ according to the DGLAP equation [4]. The other is PDFs from our previous work[5][6]: pure valence quark distributions starting from $\mu^2 = 0.064 GeV^2$ evolve according to a modified DGLAP (the GLR-MQ-ZRS) equation [7], which modifies the evolution of parton distributions with recombination effects but not included $F_2^{HT}$ in Eq. (1). We find that the negative nonlinear corrections in the GLR-MQ-ZRS equations improve the perturbative stability of the QCD evolution equation at low $Q^2$. The resulting parton distributions of proton at the leading order approximation with only four free parameters are consistent with the existing data. The nonlinear equation provides a powerful tool to connect the non-perturbative quark model with the measured structure functions.

The single curves in Ref. [1] matched the valence quark distributions. It seems that the valence quark distributions and even a pQCD analysis of them are available and reliable (at least partly) at $Q^2 < 1 GeV^2$. Therefore, as a model, we try to use the predicted
\(F_{2}^{ZRS}(x, Q^2)\) in [5] to be \(F_{2}^{LT}(x, Q^2)\) in the valence quark kinematic range, i.e.,

\[
\overline{F}_{2}^{p}(\xi, Q^2) = F_{2}^{ZRS+TMC}(\xi, Q^2) + F_{2}^{HT}(\xi, Q^2)
\]

\[
= \left[ 1 + \frac{C_{HT}(\xi, Q^2)}{Q^2} \right] F_{2}^{ZRS+TMC}(\xi, Q^2),
\]

where \(C_{HT}\) is the effective higher twist coefficient. The target mass corrections (TMC) take into account the finite mass effect of the initial nucleon and \(\xi = 2x/(1+\sqrt{1+4x^2m_p^2/Q^2})\) is the Nachtmann variable [8].

![Proton structure functions](image)

Figure 1: Proton structure functions as the function of the invariant mass squared \(W^2\) in the nucleon resonance region. Fluctuating curves: measured data by JLab [1]; Dotted curves: the scaling curves using quark-hadron duality [2]; Solid curves: Our predicted \(F_{2}^{ZRS+TMC}\).

The comparisons of \(F_{2}^{ZRS+TMC}\) with \(\overline{F}_{2}\) are presented in Fig. 1. \(F_{2}^{ZRS}(x, Q^2)\) are shown in Fig. 2, where the solid curves show the measured kinematic range of JLab data. One can find that \(F_{2}^{ZRS}(x, Q^2)\) and \(\overline{F}_{2}^{p}(x, Q^2)\) have similar shapes on both sides of the valence quark peak. This similarity between \(F_{2}^{ZRS}(x, Q^2)\) and \(\overline{F}_{2}^{p}(x, Q^2)\) strongly implies
that the valence quark distribution and its pQCD evolution are indispensable even at very low $Q^2$.

The following work is to extract the higher twist coefficients taking the values of the JLab-single curves measurement [1] and $F_2^{ZRS+TM}$ from the global analysis [5] by using Eq. (3). The obtained $C_{HT}(\xi, Q^2)$ are shown in Fig. 3, where the last three plots at high $Q^2$ are taken from [9]. What is the physical interpretation of the obtained $C_{HT}(\xi, Q^2)$ in the resonance region? Power corrections originate from the multi-parton interactions at the final state. Figure 3 shows that $C_{HT} \sim 0$ at $Q^2 = 0.07 GeV^2$, which is near the starting scale of the pQCD evolution in our previous work. A possible explanation is that the proton mainly consists of three valence quarks and all non-perturbative effects are absorbed into the definition of the initial valence quark distributions, which consequence in $C_{HT} = 0$ at $Q^2 = 0.064 GeV^2$. This small $C_{HT}$ at very low $Q^2$ coincides with a smooth
transition to the expected behavior in the real photon scattering limit $F_2(\xi, Q^2) \to 0$ for $Q^2 \to 0$, which requires

$$C_{HT}(\xi, Q^2) \to -Q^2, \text{ at } Q^2 \to 0. \quad (4)$$

We can guess that the higher twist coefficient gradually increases with the creation of new partons in pQCD evolution. However, at the same time, some of the correlations among the partons disappear under an impulse of the probe with high $Q^2$ - the impulse approximation [10]. Under the influence of the above two opposite processes, the higher twist coefficient reaches a balance in the range of $Q^2 \sim 1 - 3 \text{GeV}^2$.

![Figure 3: Higher twist coefficients $C_{HT}(\xi)$ (in GeV$^2$ units) for inelastic lepton scattering on proton target.](image)

The original quark-hadron duality [2] suggests

$$\overline{F}_2(x, Q^2) = F_2^{LT}(x, Q^2), \quad (5)$$

i.e., the higher twist contributions tend to be largely canceled by the Bloom-Gilman average [2]. Clearly, the duality in Eq. (5) is obviously violated from the plots at $Q^2 <$
1.7GeV$^2$ in Fig. 1. A direct measurement without pQCD analysis of parton distributions can not separate the higher twist corrections even at high $Q^2$. It is not a sound argument that an integral average of the measured structure function at low $Q^2$ can be identified to be a pure leading twist structure function without any higher twist contributions. Therefore, we give an alternative explanation of the quark-hadron duality shown in Eq. (3). There are two kinds of correlations among the partons: the short distance correlation and the long distance correlation. They are related to the higher twist effects in DIS process and the resonance structure of nucleon, respectively. The integral average of the resonance curves cancels the long distance correlations and the resulting structure functions are related to parton distributions with only the short distance corrections - the higher twist corrections to DGLAP equations.

We calculated $F_2^{ZRS}$ at the $LL(Q^2)$ approximation, where the high order corrections of $\alpha_s$ are neglected. Our predicted distributions are comparable with the data at $Q^2 > 1GeV^2$ [5], it implies that the high order effects of $\alpha_s^n$ are absorbed into a free parameter $R$ in the non-linear terms of the evolution equation.

The factorization in Eq. (1) is not proved at low $Q^2$ and small $x$, where the correlations between initial and final states is not negligible. However, we can use some phenomenological model to mimic its contribution. We will discuss this elsewhere.

In summary, using the JLab data measured at low $Q^2$, we separate the contributions of parton distributions from higher twist corrections to lepton-proton DIS process in the resonance region. We get the parton distributions at low $Q^2$ using the input valence quark distributions at 0.064GeV$^2$ based on the modified DGLAP equation. The concept of valence quarks and valence quark distributions are indispensable even at $Q^2 < 1GeV^2$.
in order to understand the nucleon structure quantitatively. The quark-hadron duality should be modified as Eq. (3). The higher twist corrections can not be neglected to study the quark-hadron duality.

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