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Analysis of F_2 and Drell-Yan data for nuclear parton distribution functions

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Abstract. We report recent studies on a χ^2 analysis of nuclear DIS and Drell-Yan data for obtaining optimum nuclear parton distribution functions. The initial distributions at Q^2=1 GeV^2 are expressed by a number of parameters, which are then determined by minimizing χ^2 in comparison with the data. Obtained distributions are discussed, and possible studies at a neutrino factory are suggested.

1. Introduction

Parton distribution functions (PDFs) are important for testing both perturbative and nonperturbative aspects of QCD. In particular, the x dependence is associated with nonperturbative physics, so that the PDF studies are useful for establishing a realistic picture of hadron structure. Furthermore, they are important for applications, for example, to high-energy heavy-ion reactions and neutrino oscillation experiments. It is, however, in an unfortunate situation that there are only a few studies on nuclear parton distribution functions (NPDFs).

There have been many model dependent studies on the NPDFs; however, the first serious model independent studies, as far as the author is aware, were reported by Eskola, Kolhinen, Ruuskanen, and Salgado (EKRS) [1]. They divided the x region into three parts and tried to obtain the optimum distributions to explain high-energy experimental data. The unpolarized and polarized PDFs in the nucleon have been obtained by χ^2 analyses. Such a χ^2 analysis method was developed for the nuclear case in Ref. [2]. This analysis is partly intended to understand how well the NPDFs are determined solely by the DIS F_2^A/F_2^D data, other data such as those of Drell-Yan (DY) are not included. It leads to somewhat different distributions from the EKRS ones. Since the first publication in Ref. [2], we have been working on the analysis including the DY and Q^2 dependent data. We report preliminary analysis results.

2. Analysis and results

For the parametrization of the NPDFs, the initial distributions are assumed as

$$f_i^A(x,Q_0^2) = w_i(x,A,Z)\, f_i(x,Q_0^2), \tag{1}$$

at a fixed Q^2 point (Q_0^2=1 GeV^2). The large x ($x > 1$) nuclear distributions cannot be expressed by this form, but there is no significant DIS data in such an x region.

Therefore, this functional form does not sacrifice any important physics at this stage. The subscript i denotes the distribution type: i=u_v, d_v, $\bar{q}$, or g. The function f_i is the corresponding distribution in the nucleon. Nuclear modification is taken into account by the weight function w_i. Because the nuclear effects are typically less than 20-30%, it is more practical to parametrize w_i instead of f_i^A itself. Therefore, the key point of our analysis is how to take the functional form of w_i. In the present analysis, the A dependence is assumed to be proportional to $1/A^{1/3}$ for simplicity, and the x dependence is taken in the cubic functional form:

$$w_i(x, A, Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right) \frac{a_i(A, Z) + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}. \tag{2}$$

The parameters a_i, b_i, c_i, d_i, and β_i are determined by a χ^2 analysis. However, three of them are fixed by the conservation conditions of baryon-number, charge, and momentum. We also have been investigating more complicated A dependence, but significant results are not obtained yet.

The NPDFs are evolved to experimental Q^2 points by the usual DGLAP equations. We use the data of the structure function ratios $F_2^A/F_2^{A'}$ together with the Drell-Yan cross-section ratios $\sigma_{DY}^A/\sigma_{DY}^{A'}$. In comparison of the theoretical ratios with the data, the total χ^2 is calculated by

$$\chi^2 = \sum_j \frac{(R_j^{data} - R_j^{theo})^2}{(\sigma_j^{data})^2}. \tag{3}$$

Here, R is $F_2^A/F_2^{A'}$ or $\sigma_{DY}^A/\sigma_{DY}^{A'}$, where A' is not only the deuteron but also other nuclei: lithium, beryllium, and carbon. These structure functions and the DY cross sections are calculated in the leading order. The experimental error is given by systematic and statistical errors as $(\sigma_j^{data})^2 = (\sigma_j^{sys})^2 + (\sigma_j^{stat})^2$.

Obtained optimum weight functions are shown for the calcium nucleus in Fig. 1 at Q^2=1 GeV^2. The solid, dashed, and dotted curves indicate valence-quark, antiquark, and gluon weight functions, respectively. The functional forms of the valence-quark and antiquark distributions are similar. The large x valence distribution is determined by the F_2 data. The small x antiquark distribution is fixed by the F_2 shadowing data. In the middle region ($x \sim 0.1$), both F_2 and DY data play an important role. In particular, the DY data indicate small modification of the antiquark distribution in this x region, so that the F_2 antishadowing should be explained by the bump of the valence-quark distribution. Then, because of this bump together with the baryon-number and charge conservations, the valence-quark distribution shows shadowing behavior at small x. As far as the valence-quark and antiquark distributions are concerned, the obtained distributions are similar to those of the EKRS parametrization [1]. Because the DY data are added, the distributions in Fig. 1 are different from those of the 2001 version [2]. The gluon distribution is difficult to be determined in the leading-order analysis, especially in the large x region. Therefore, the obtained gluon distribution at medium x is different from the EKRS one.

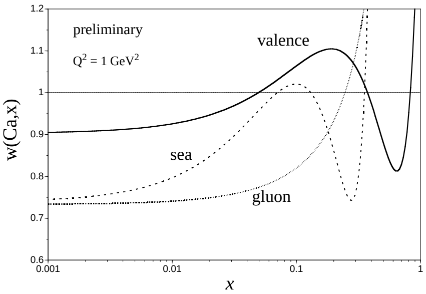

Figure 1. Nuclear modification of the parton distribution functions at Q^2=1 GeV^2.

3. Comments on neutrino reactions

Neutrino deep inelastic scattering data have been obtained; however, no serious nuclear effect is investigated so far. In future, it could be investigated by the NuMI [3] and neutrino-factory projects. It is especially important to investigate the parity-violating structure function F_3. A combination of the F_3 structure functions is given by $[\,F_3^{\nu(p+n)} + F_3^{\bar{\nu}(p+n)}\,]/4 \approx u_v + d_v$, which probes the valence-quark distributions directly. Because the valence distributions are known by the electron and muon scattering data of F_2 at large x, the advantage of a future neutrino facility is to investigate the small x region. In particular, the valence shadowing is not known although the F_2 shadowing, namely the antiquark shadowing, is well investigated. The valence-quark behavior at small x is restricted by the baryon-number and charge conservations; however, these conditions are not enough to determine the accurate functional form at small x.

In Fig. 2, we show the valence-quark modification at Q^2=1 GeV^2 by our parametrization as an example. The dashed curve is obtained by using the first analysis results of 2001 [2]. The first version did not include the DY data, so that the F_2 anti-shadowing at $x \sim 0.2$ is explained partly by the antiquark distribution and valence antishadowing is not large at $x \sim 0.2$. Consequently, the small x modification becomes small. The solid curve indicates the recent parametrization result by including the DY data [2]. In this case, the antishadowing part is explained mainly by the valence antishadowing. Therefore, it shows shadowing behavior at small x in order to satisfy the baryon-number and charge conservations. There are also model studies on the possible valence shadowing [4].

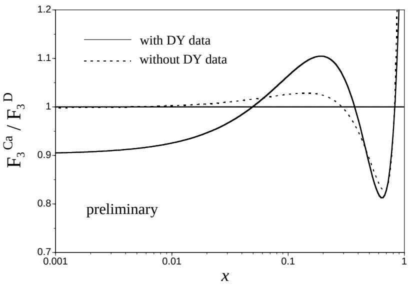

Figure 2. Nuclear modification of the valence-quark distributions in the calcium.

The detailed studies of the valence-quark distributions are also connected to electroweak physics. For example, the Paschos-Wolfenstein relation is useful for measuring $sin^2\theta_W$, and the current NuTeV data indicate a significant deviation from the standard model prediction. It was pointed out in Ref. [5] that such a deviation could be, at least partially, due to the nuclear modification difference between up- and down-quark distributions. We should be able to find the difference by neutrino-factory measurements.

References

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