A STATISTICAL APPROACH FOR POLARIZED PARTON DISTRIBUTIONS*

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A global next-to-leading order QCD analysis of unpolarized and polarized deep-inelastic scattering data is performed with parton distributions constructed in a statistical physical picture of the nucleon. The chiral properties of QCD lead to strong relations between quarks and antiquarks distributions and the importance of the Pauli exclusion principle is also emphasized. We obtain a good description, in a broad range of x and Q^2, of all measured structure functions in terms of very few free parameters. Forthcoming experiments at RHIC–BNL are sensitive tests of the statistical model for the behavior of the $\bar{d}(x)/\bar{u}(x)$ ratio for $x \geq 0.2$ and for the magnitude and sign of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$.

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1. Introduction

Deep Inelastic Scattering (DIS) of leptons on hadrons has been extensively studied, over the last twenty years or so, both theoretically and experimentally, to extract the Polarized Parton Distributions (PPD) of the nucleon. As it is well known, the unpolarized light quarks (u, d) distributions are fairly well determined. Moreover, the data exhibit a clear evidence for a flavor-asymmetric light sea, *i.e.* $\bar{d} > \bar{u}$, which can be understood in terms of the Pauli exclusion principle, based on the fact that the proton contains two u quarks and only one d quark. Larger uncertainties still persist for the gluon (G) and the heavy quarks (s, c) distributions. From the more restricted amount of data on polarized structure functions, the corresponding polarized gluon and s quark distributions $(\Delta G, \Delta s)$ are badly constrained and we just begin to uncover a flavor asymmetry, for the corresponding polarized light sea, namely $\Delta\bar{u} \neq \Delta\bar{d}$. Whereas the signs of the polarized light

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quarks distributions are essentially well established, $\Delta u > 0$ and $\Delta d < 0$, this is not the case for $\Delta\bar{u}$ and $\Delta\bar{d}$. The objective of this report, essentially based on Ref. [1], is to construct a complete set of polarized parton (all flavor quarks, antiquarks and gluon) distributions and, in particular, we will try to clarify this last point on the polarized light sea. Our motivation here is to use the statistical approach to build up: q_i, Δq_i, $\bar{q}_i$, $\Delta\bar{q}_i$, G and ΔG, by means of a very small number of free parameters. A flavor separation for the unpolarized and polarized light sea is automatically achieved in a way dictated by our approach.

2. Construction of the PPD in the statistical approach

In the statistical approach the nucleon is viewed as a gas of massless partons (quarks, antiquarks, gluons) in equilibrium at a given temperature in a finite size volume. Like in our earlier works on the subject [2], we propose to use a simple description of the parton distributions $p(x)$, at an input energy scale Q_0^2, proportional to

$$\left[\exp\left[\frac{(x - X_{0p})}{\bar{x}}\right] \pm 1\right]^{-1}, \tag{2.1}$$

the *plus* sign for quarks and antiquarks, corresponds to a Fermi–Dirac distribution and the *minus* sign for gluons, corresponds to a Bose–Einstein distribution. Here X_{0p} is a constant which plays the role of the *thermodynamical potential* of the parton p and $\bar{x}$ is the *universal temperature*, which is the same for all partons. Since quarks carry a spin 1/2, it is natural to consider that the basic distributions are $q_i^{\pm}(x)$, corresponding to a quark of flavor i and helicity parallel or antiparallel to the nucleon helicity. This is the way we will proceed. Clearly one has $q_i = q_i^+ + q_i^-$ and $\Delta q_i = q_i^+ - q_i^-$ and similarly for antiquarks and gluons.

From the chiral structure of QCD, we have two important properties which allow to relate quark and antiquark distributions and to restrict the gluon distribution:

— The potential of a quark q_i^h of helicity h is opposite to the potential of the corresponding antiquark $\bar{q}_i^{-h}$ of helicity $-h$

$$X_{0q}^h = -X_{0\bar{q}}^{-h}\,. \tag{2.2}$$

— The potential of the gluon G is zero

$$X_{0G} = 0\,. \tag{2.3}$$

From well established features of the u and d quark distributions extracted from DIS data, we anticipate some simple relations between the potentials:

— $u(x) > d(x)$, therefore one can expect $X^+_{0u} + X^-_{0u} > X^+_{0d} + X^-_{0d}$,
— $\Delta u(x) > 0$, therefore $X^+_{0u} > X^-_{0u}$,
— $\Delta d(x) < 0$, therefore $X^-_{0d} > X^+_{0d}$.

So we expect X^+_{0u} to be the largest thermodynamical potential and X^+_{0d} the smallest one. In fact, we have found the following ordering

$$X^+_{0u} > X^-_{0d} \sim X^-_{0u} > X^+_{0d}\,. \tag{2.4}$$

Eq. (2.4) is consistent with the previous determinations of the potentials [2]. By using Eq. (2.2), this ordering leads immediately to some important consequences for antiquarks, namely

(i) $\bar{d}(x) > \bar{u}(x)$, the flavor symmetry breaking which also follows from the Pauli exclusion principle, as recalled above. This was already confirmed by the violation of the Gottfried sum rule [3, 4];

(ii) $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$, which remain to be checked and this will be done in hadronic collisions at RHIC–BNL (see Sec. 3).

Note that, from Eq. (2.4) one has $u^-(x) \sim d^-(x)$ which implies

$$\Delta u(x) - \Delta d(x) \sim u(x) - d(x)\,. \tag{2.5}$$

As a consequence of Eq. (2.2), we also have $\bar{u}^+(x) \sim \bar{d}^+(x)$. This leads obviously to

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) \sim \bar{d}(x) - \bar{u}(x) \tag{2.6}$$

so the flavor symmetry breaking is almost the same for unpolarized and polarized antiquark distributions.

Let us now complete the description of our parametrization. The small x region is characterized by a rapid rise as $x \to 0$ of the distribution, which should be dominated by a universal diffractive term, flavor and helicity independent, coming from the Pomeron universality. Therefore, we must add a term of the form $\tilde{A}x^{\tilde{b}}/[\exp(x/\bar{x})+1]$, where $\tilde{b} < 0$ and $\tilde{A}$ is a normalization constant. So for the light quarks $q = u,\ d$ of helicity $h = \pm$, at the input energy scale $Q_0^2 = 4\mathrm{GeV}^2$, we take

$$xq^h\left(x, Q_0^2\right) = \frac{AX^h_{0q}x^b}{\exp\left[\left(x - X^h_{0q}\right)/\bar{x}\right] + 1} + \frac{\tilde{A}x^{\tilde{b}}}{\exp(x/\bar{x}) + 1}\,, \tag{2.7}$$

and similarly for the light antiquarks

$$x\bar{q}^h\left(x, Q_0^2\right) = \frac{\bar{A}(X^{-h}_{0q})^{-1}x^{2b}}{\exp\left[\left(x + X^{-h}_{0q}\right)/\bar{x}\right] + 1} + \frac{\tilde{A}x^{\tilde{b}}}{\exp(x/\bar{x}) + 1}\,. \tag{2.8}$$

For the heavy quarks (s, c), whose unpolarized and polarized distributions are unknown or poorly known, we take a simple ansatz (see Ref. [1]). Concerning the gluon distribution, as indicated above, we use a Bose–Einstein expression given by

$$xG\left(x,Q_0^2\right) = \frac{A_G x^{b_G}}{\exp(x/\bar{x})-1}\,, \tag{2.9}$$

with a vanishing potential and the same temperature $\bar{x}$. It is also reasonable to assume that for very small x, $xG(x,Q_0^2)$ has the same behavior as $x\bar{q}(x,Q_0^2)$, so we will take $b_G = 1+\tilde{b}$. Since the normalization constant A_G is determined from the momentum sum rule, our gluon distribution has no free parameter. For the sake of completeness, we also need to specify the polarized gluon distribution and we take the particular choice

$$x\Delta G\left(x,Q_0^2\right) = 0\,, \tag{2.10}$$

consistently with Eq. (2.3). To summarize our parametrization involves a total of *eight* free parameters

$$\bar{x}\,,\ X_{0u}^{+}\,,\ X_{0u}^{-}\,,\ X_{0d}^{-}\,,\ X_{0d}^{+} b\,,\ \tilde{b}\ \text{and}\ \tilde{A}\,. \tag{2.11}$$

These parameters, are determined by a fitting procedure described in Ref. [1].

3. Experimental tests for unpolarized and polarized DIS

We first consider μp and ep DIS for which several experiments have yielded a large number of data points on the structure function $F_2^p(x,Q^2)$. We have compared our calculations with fixed target measurements NMC, BCDMS and E665, which cover a rather limited kinematic region in Q^2 and also with the data at HERA from the H1 and ZEUS Collaborations. These last data cover a very large Q^2 range, up to $Q^2 = 10^4\text{GeV}^2$ or so and probe the very low x region which is dominated by the rising behavior of the universal diffractive term. We compare our results with the data on Fig. 1. We also have a very good description of the neutron structure function $F_2^n(x,Q^2)$ data, as well as for the $xF_3^{\nu N}(x,Q^2)$ structure function, extracted from the high statistics νN DIS data from CCFR(see Ref. [1]).

Let us come back to the important question of the flavor asymmetry of the light antiquarks. Our determination of $\bar{u}(x,Q^2)$ and $\bar{d}(x,Q^2)$ is perfectly consistent with the violation of the Gottfried sum rule, for which we found $I_G = 0.2493$ for $Q^2 = 4\text{GeV}^2$. Nevertheless there remains an open problem with the x distribution of the ratio $\bar{d}/\bar{u}$ for $x \geq 0.2$, in connection with the E866/NuSea Collaboration [5]. They have released the final results corresponding to the analysis of their full data set of Drell–Yan yields from an $800\,\text{GeV}/c$ proton beam on hydrogen and deuterium targets and they obtain the ratio $\bar{d}/\bar{u}$, for $Q^2 = 54\,\text{GeV}^2$. The errors are large in the high x region and one way to clarify the situation is to measure the ratio of the unpolarized cross sections for the production of W^+ and W^- in pp collisions, which will directly probe the behavior of the $\bar{d}(x)/\bar{u}(x)$ ratio. Interesting predictions of the statistical model, which are accessible at RHIC–BNL, are given in [1].

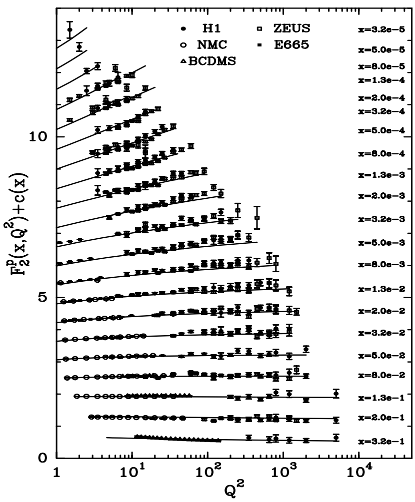

Fig. 1. $F_2^p(x,Q^2)$ as function of Q^2 for fixed x, $c(x) = 0.6(i_x - 0.4)$, $i_x = 1 \rightarrow x = 0.32$, re-binned data H1, ZEUS, E665, NMC, BCDMS. (Presentation of data, courtesy of R. Voss).

Since our approach is based on the direct construction of the quark and antiquark distributions of a given helicity $q_i^{\pm}$ and $\bar{q}_i^{\pm}$, from the previous results we immediately obtained Δq_i and $\Delta \bar{q}_i$ for each flavor, which enter in the definition of the polarized structure functions $g_1^{p,d,n}(x,Q^2)$. In Fig. 2 we show a data compilation of $g_1^{p,d,n}(x,Q^2)$ from different current experi-

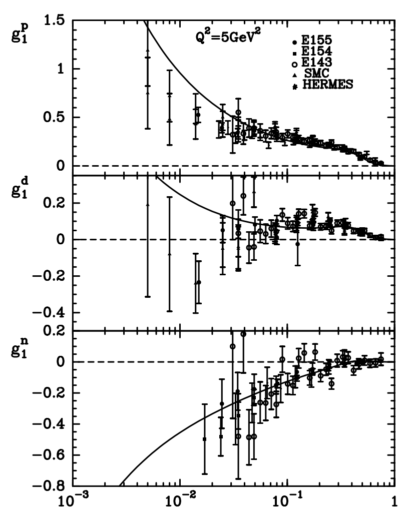

Fig. 2. $g_1^{p,d,n}(x,Q^2)$ *versus* x for different Q^2 values, from E155, E154, E143, SMC, HERMES. The curves correspond to our model predictions at $Q^2 = 5\text{GeV}^2$.

ments on proton, deuterium and helium targets, evolved at a fixed value $Q^2 = 5\text{GeV}^2$. The x dependence is in fair agreement with our results and we predict, in the small x region, a fast rising behavior for g_1^p and a fast decreasing behavior for g_1^n, due to the antiquark contributions. This cannot be tested so far, due to the lack of precise data. Preliminary data with large errors from HERMES for $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ at $Q^2 = 2.5\text{GeV}^2$, were presented at this workshop [6] and the comparison with our model prediction is displayed on Fig. 3. Finally, a good flavor separation can be achieved by measuring the parity-violating asymmetry in $W^\pm$ production at RHIC–BNL. Our predictions are shown on Fig. 4. The trend of $A_L^{PV}(W)$ can be easily understood, for example at $\sqrt{s} = 500\text{GeV}$ near $y = +1$, $A_L^{PV}(W^+) \sim \Delta u/u$ and $A_L^{PV}(W^-) \sim \Delta d/d$, evaluated at $x = 0.435$. Similarly for near $y = -1$, $A_L^{PV}(W^+) \sim -\Delta\bar{d}/\bar{d}$ and $A_L^{PV}(W^-) \sim -\Delta\bar{u}/\bar{u}$, evaluated at $x = 0.059$.

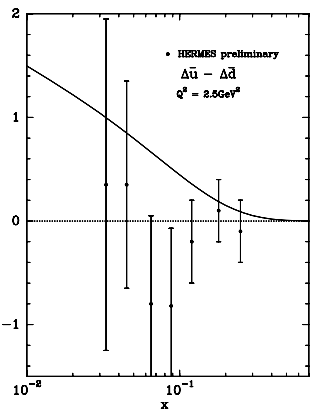

Fig. 3. Our model prediction at $Q^2 = 2.5\,\text{GeV}^2$ compared to preliminary data from HERMES [6].

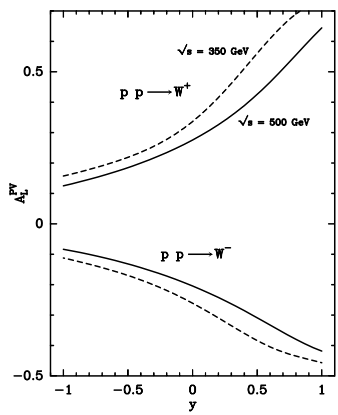

Fig. 4. The parity violating asymmetry A_L^{PV} for $pp \to W^\pm$ production *versus* the W rapidity at $\sqrt{s} = 350$ GeV (dashed curve) and $\sqrt{s} = 500$ GeV (solid curve).

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