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POLARIZED STRUCTURE FUNCTIONS UP TO COLLIDER ENERGIES

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ABSTRACT

We present a new set of spin-dependent structure functions for quarks and gluons inside a polarized nucleon. This is the only available set which satisfies all the sum rules and analytic requirements and is valid in the kinematic range $10^{-5} < x < 0.9$ and $5 < Q^2 < 5 \cdot 10^8 \text{ GeV}^2$, the effects of heavier flavours being taken into account.

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A trustworthy determination of the nucleon structure functions is required in order to estimate production rates in future hadron colliders at very high energies. Given these structure functions at low energies, perturbative QCD enables us to predict their Q^2 behaviour which gives, through hadron hard collisions, an insight into constituent interactions. A fair amount of theoretical work has been devoted to the determination of the unpolarized nucleon structure functions¹⁾ for quarks $q(x, Q^2)$ and gluons $G(x, Q^2)$, where the kinematical variables lie in the following appropriate range, $10^{-5} < x < 0.9$ and $5 < Q^2 < 5 \cdot 10^8$ GeV². The essential features of this phase space domain are the very small x values and the enormous Q^2 values. Indeed, the small x region is crucial because it is well known that, as Q^2 increases, since there are more and more partons with a low momentum, the structure functions become more important for small x . We also recall that, in spite of some uncertainties in the very small x region, gluons are expected to dominate over quarks and to provide the bulk of the high $p_{\perp}$ cross-sections in some specific kinematic regions. The aim of this letter is to produce a reliable set of polarized structure functions in the above-mentioned x and Q^2 ranges, suitable for the determination of the size of spin effects up to supercollider energies.

For a given parton (quark or gluon), let us denote by $f_{\pm}(x, Q^2)$ the parton distributions in a polarized nucleon either with helicity parallel (+) or anti-parallel (-) to the parent nucleon helicity. We define as usual the quark and gluon helicity asymmetries $\Delta q = q_+ - q_-$ and $\Delta G = G_+ - G_-$. As for the unpolarized case, the evolution of the helicity asymmetries $\Delta f(x, Q^2)$ is usually studied in perturbative QCD by means of the Altarelli-Parisi equations²⁾ which led us, in previous work³⁾, to an analytic parametrization of the x and Q^2 dependences. However, these results must be revised and the limitations of this earlier analysis are twofold. First, the procedure we used was based on a direct resolution of these equations for the unpolarized case⁴⁾, which is not justified for small x . More specifically, our results⁵⁾, both for unpolarized and polarized cases, were valid for $x > 0.03$ only, which is insufficient for making reliable predictions at very high energies, where we know that quarks and gluons are concentrated in the low x kinematical region. Second, the number of effective flavours was taken to be $N_f = 3$ for all Q^2 , but clearly at future colliders one will reach huge Q^2 values and one should include the effects of heavier quarks.

Concerning the first point, the method we are using here is based on the moments of the distributions defined as

$$f_n(Q^2) = \int_0^1 dx \, x^{n-1} f(x, Q^2) \quad (1)$$

where f denotes either unpolarized or polarized parton distributions. Given the low energy input $f(x, Q_0^2)$, for example at $Q_0^2 = 5 \text{ GeV}^2$, we can calculate $f_n(Q_0^2)$ and then solve the Altarelli-Parisi equations for the moments to get $f_n(Q^2)$ for any $Q^2 > Q_0^2$. The x dependence is obtained from the inverse Mellin transform

$$f(x, Q^2) = \int_{-i\infty}^{+i\infty} \frac{dn}{2i\pi} x^{-n} f_n(Q^2) \quad (2)$$

requiring an analytic continuation to complex n for $f_n(Q^2)$ and the use of an appropriate contour in the complex n plane⁵⁾. For the second point, the effect of heavier flavours was included through the running coupling constant $\alpha_s(Q^2)$. Below the charm threshold, i.e., for $N_f = 3$, we take

$$\alpha_s^{-1}(Q^2) = \beta_0^{(N_f)} \ln Q^2/\Lambda^2 \quad \text{for } 0 < Q^2 \leq 4m_c^2 \quad (3)$$

where

$$\beta_0^{(N_f)} = (33 - 2N_f) / 12\pi$$

whereas above it, we should take the corresponding N_f value ($N_f = 4, 5$ or 6) and use a different energy scale, such that

$$\alpha_s^{-1}(Q^2) = \beta_0^{(N_f)} \ln Q^2/4m_i^2 + \alpha_s^{-1}(4m_i^2) \quad \text{for } 4m_i^2 \leq Q^2 \leq 4m_{i+1}^2 \quad (4)$$

($i = c, b, t$)

This choice⁶⁾ allows the change of slope of $\alpha_s(Q^2)$ as new thresholds are passed and ensures that it is a continuous function of Q^2 .

The results for the gluon are shown in Figs. 1a and 1b for a given Q^2 , and we see that with $N_f = 3$, compared to $N_f = 6$, the distributions are underestimated

for small x and overestimated for x above 10^{-2} or so. We are fairly confident in these results because for sufficiently small x we recover the approximate behaviour mentioned in an earlier paper⁷⁾, given by

$$xG(x, S) \sim \exp \left[2 \sqrt{R_+ S \ln \frac{1}{x}} \right]$$

and

$$\Delta G(x, S) \sim \exp \left[2 \sqrt{\Delta R_+ S \ln \frac{1}{x}} \right] \quad (5)$$

where $S = \ln t/t_0$ with $t = \ln Q^2/\Lambda^2$ and $R_+ = 1.71$, $\Delta R_+ = 2.91$ for $N_f = 6$. We also recall that the gluon helicity asymmetry is constrained by an important sum rule derived recently⁷⁾, analogous to momentum conservation for the unpolarized distributions. According to this sum rule, which involves the v moments, the following linear combination

$$\Delta \Sigma_v(Q^2) + (\Delta a_v^+) \Delta G_v(Q^2) \quad (6)$$

is independent of Q^2 . Σ is the singlet quark distribution, v and Δa_v^+ are such that $1 < v < 2$ and $0 < \Delta a_v^+ < 1$ and depend on the value of N_f . This sum rule is now fully satisfied and provides a consistency check of our calculations.

In Fig. 2a, we show the gluon polarization $\Delta G(x)/G(x)$ for different Q^2 values. We see that at low energy this polarization is less than 20%, but it rises for all x with energy. Such a spectacular effect which was observed previously and widely discussed^{3), 6)} is even more striking now with a very rapid rise, mainly in the low x region. The valence quark polarization $\Delta V(x)/V(x)$ is shown in Fig. 2b. It also grows with Q^2 but does not change drastically from the low energy input. We note that both the gluon and valence quark polarizations hardly increase after the top threshold is passed. The choice of the low energy input is not unique³⁾ due to some uncertainty in the experimental data, but this does not seriously affect the predictions at high energies for the gluon and valence quark polarizations. This is not the case for the sea quark polarization, which can be either positive or negative. Anyway, this polarization is of the order of 10%, and the sea contribution is small and remains largely below the other parton distributions.

To conclude, this accurate determination of the polarized structure functions will be a motivation to undertake a systematic study of spin effects in a multi-TeV collider where gluons are expected to dominate. In particular, the growth with Q^2 of the gluon polarization inside a polarized nucleon, which is a significant prediction of perturbative QCD, should be further investigated. It can be detected in jet production in hadron colliders, where gluon-quark and gluon-gluon interactions are expected to prevail, and also in lepton-hadron colliders where heavy quark production may be dominated by photon-gluon fusion. Also, the exploration of the tail of the gluon distributions might be another possibility to reveal new physics.

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FIGURE CAPTIONS

- Fig. 1a : Gluon distribution $xG(x)$ as a function of x for $Q^2 = 5 \cdot 10^4 \text{ GeV}^2$, $N_f = 3$ (dashed curve) and $N_f = 6$ (solid curve).
- Fig. 1b : Same as Fig. 1a for the gluon helicity asymmetry $x\Delta G(x)$.
- Fig. 2a : Gluon polarization $\Delta G(x)/G(x)$ as a function of x for $Q^2 = 5 \text{ GeV}^2$ (dashed-dotted curve), $Q^2 = 5 \cdot 10^4 \text{ GeV}^2$ (dashed curve) and $Q^2 = 5 \cdot 10^8 \text{ GeV}^2$ (solid curve).
- Fig. 2b : Same as Fig. 2a for the valence quark polarization $\Delta V(x)/V(x)$.

Fig. 1a

Fig. 1b

Fig. 2a

Fig. 2b