Polarized parton distributions from charged–current deep-inelastic scattering

G. Ridolfi

INFN Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy

Abstract. We investigate the capabilities of a neutrino factory in the determination of polarized parton distributions from charged–current deep–inelastic scattering experiments, with special attention to the accuracy of this kind of measurements. We show that a neutrino factory would allow to distinguish between different theoretical scenarios for the proton spin structure.

Our present knowledge [1] on nucleon structure functions for polarized deep-inelastic scattering (DIS) originates from the observation of neutral-current phenomena. In this context, a precise determination of individual flavor distributions is very difficult, because of the weak sensitivity to the polarized strange quark density. Furthermore, quark-antiquark separation is impossible, since only C-even polarized parton distributions $\Delta q^+ = \Delta q + \Delta\bar{q}$ can be measured by this kind of experiments. Neutrino factories offer the oppurtunity of measuring both parity-conserving and parity-violating structure functions, thus allowing an accurate determination of C-odd parton densities $\Delta q^- = \Delta q - \Delta\bar{q}$.

A central issue in physics of polarized nucleons is to explain the unexpected smallness of the axial charge

$$a_0(Q^2) = \int_0^1 dx\,\left(\Delta\Sigma^+ - \frac{n_f\alpha_s}{2\pi}\,\Delta g\right), \tag{1}$$

where Δg is the polarized gluon distribution, and $\Delta\Sigma^+ = \Delta u^+ + \Delta d^+ + \Delta s^+$. Present data indicate that a_0 is compatible with zero, but values as large as $a_0(10\ \mathrm{GeV}^2) = 0.3$ are not excluded. A possible theoretical interpretation is to assume that a cancellation between a large (scale–independent, or AB–scheme) $\Delta\Sigma^+$ and a large Δg takes place. In this case, $|\Delta u^+|, |\Delta d^+| \gg |\Delta s^+|$ (in the AB–scheme), as expected in the quark model. This is usually called the 'anomaly' scenario. Alternatively, one may assume that Δg is indeed small, and that Δs^+ is large and negative. This might be explained by invoking non–perturbative, instanton–like vacuum configuration ('instanton' scenario). In this case, $\Delta s = \Delta\bar{s}$. In the 'skyrmion' scenario, Δs^+ large, but Δs is significantly different from $\Delta\bar{s}$. Future experiments will aim at improving the accuracy in the determination of the axial charge and of the polarized gluon distribution. Furthermore, it will be important to understand whether Δs is large, compared to the light flavor distributions, and how different it is from $\Delta\bar{s}$. In the following we will explore the potential of a neutrino factory in answering these questions.

Present experimental information on polarized parton densities is summarized in the first two columns of table 1, where η_Σ, η_3 and η_8 are the first moments of $\Delta u^+ + \Delta d^+ + \Delta s^+$, $\Delta u^+ - \Delta d^+$ and $\Delta u^+ + \Delta d^+ - 2\Delta s^+$ respectively (all of them

Table 1. Fits to neutral–current polarized DIS data (columns 1-2) and to the real and fake data (columns 3-5).

	generic fit	$\eta_g = 0$ fit	'anomaly' refit	'instanton' refit	'skyrmion' refit
η_Σ	0.38 ± 0.03	0.31 ± 0.01	0.39 ± 0.01	0.321 ± 0.006	0.324 ± 0.008
η_g	0.79 ± 0.19	0	0.86 ± 0.10	0.20 ± 0.06	0.24 ± 0.08
η_3	1.110 ± 0.043	1.039 ± 0.029	1.097 ± 0.006	1.052 ± 0.013	1.066 ± 0.014
η_8	0.579	0.579	0.557 ± 0.011	0.572 ± 0.013	0.580 ± 0.012
η_u	0.777	0.719	0.764 ± 0.006	0.722 ± 0.010	0.728 ± 0.009
η_d	-0.333	-0.321	-0.320 ± 0.008	-0.320 ± 0.009	-0.325 ± 0.009
η_s	-0.067	-0.090	-0.075 ± 0.008	-0.007 ± 0.007	-0.106 ± 0.008
a_0	0.183 ± 0.030	0.284 ± 0.012	0.183 ± 0.013	0.255 ± 0.006	0.250 ± 0.007

are scale-independent quantities in the AB scheme), and η_g is the first moment of the polarized gluon distribution at $Q^2 = 1$ GeV^2. The value of a_0 at $Q^2 = 10$ GeV^2 is also given. The second column corresponds to a fit with η_g forced to zero. Previous analyses show that this value, although disfavoured by the data, can only be excluded at about two standard deviations. The last three rows in table 1 show the values of the first moments of Δq^+ at $Q^2 = 1$ GeV^2 for $q = u, d, s$.

In order to estimate the impact of charged–current DIS data from a ν factory on our knowledge of the proton spin structure, we proceed as follows. We assume that both ν and $\bar{\nu}$ beams will be available, and therefore that the four structure functions $g_1^{W^\pm}, g_5^{W^\pm}$ will be measured (at leading twist, charged–current polarized DIS can be described in terms of two independent structure functions). Under this assumption, taking suitable combinations of structure functions for different targets below and above the charm threshold, a complete separation of all four flavors and antiflavors is possible (see ref. [2] for the details).

We have computed the expected errors on the measurements of g_1 and g_5 (for proton and deuteron targets) in a region of the x, Q^2 plane compatible with the features of the device. With the parameter choice of ref. [2], this corresponds to about $0.01 \le x \le 0.7$ and $1\,\mathrm{GeV}^2 \le Q^2 \le 100\,\mathrm{GeV}^2$. The neutrino beam is assumed to be generated by a muon beam with energy $E_\mu = 50$ GeV and number of muon decays per year $N_\mu = 10^{20}$.

We have produced sets of "fake" data for charged–current structure functions according to three different assumptions:

(i) generic fit of table 1 and $\Delta\bar{s} = 0$ (anomaly scenario);

(ii) $\eta_g = 0$ fit of table 1 and $\Delta\bar{s} = \Delta s$ (instanton scenario);

(iii) $\eta_g = 0$ fit of table 1 and $\Delta\bar{s} = 0$ (skyrmion scenario).

In all three cases, we have fixed $\Delta\bar{u} = \Delta\bar{d} = 0$, consistently with the indications of semi-inclusive DIS data, and with positivity constraints. The fake data were then gaussianly distributed about their central values, with the errors determined as explained above. In this way, a total of 8 sets of fake data (g_1 and g_5 with ν and $\bar{\nu}$ beams and proton or deuteron targets) were generated, with ~ 70 data points in each set (the neutral–current real data correspond to 176 points). Real and fake data were then fitted by means of a NLO evolution code [2], based on previous work for neutral–current structure functions [3]. The results are shown in the last three columns of table 1. The rows labelled η_u, η_d and η_s now give the best–fit values and errors on the first moments of Δq^- for u, d, s.

Comparing these values with those of our original fits (first and second columns), we see that the precision on the singlet quark first moment is significantly improved by the charged–current data: the error on the first moment of $\Delta\Sigma^+$ is now of a few percent in comparison to about 10% with neutral–current DIS. With this accuracy, the 'anomaly' scenario can be experimentally distinguished from other scenarios, at the level of several standard deviations. This is also reflected by the improvement in the precision on the gluon first moment.

The determination of the singlet axial charge is improved by an amount comparable to the improvement in the determination of the singlet quark first moment. It will be possible to establish at the level of a few percent whether the axial charge differs from zero or not. The determination of the isotriplet axial charge is also significantly improved: the improvement is comparable to that on the singlet quark. This would allow an extremely precise test of the Bjorken sum rule, and an accurate determination of the strong coupling. Finally, the octet C–even combination is now also determined with an uncertainty of a few percent. Therefore, the strange C–even component can be determined with an accuracy which is better than 10%. Comparing this direct determination of the octet axial charge to the value obtained from baryon decays would allow a test of different existing models of SU(3) violation.

Let us now consider the results for the first moments of the C–odd distributions. We see that in the case of u and d quarks they can be measured with an accuracy of a few percent, just sufficient to establish whether the up and down antiquark distributions, which are constrained by positivity to be quite small, differ from zero, and whether they are equal to each other or not. Furthermore, the strange C–odd component can be determined at a level of about 10%, which is enough to distinguish between the two cases $\Delta s^- \sim 0$ and $\Delta s^- \sim \Delta s^+$. The instanton and skyrmion scenarios can thus also be distinguished at the level of several standard deviations.

In conclusion, we have explored the capabilities of a neutrino factory in the study of polarized DIS. With such a facility the accuracy in the determination of the first moments of C–even distributions can be improved by about an order of magnitude with respect to the current uncertaintiesthus allowing a definitive confirmation or refutation of the 'anomaly' scenario for the proton spin structure, compared to the 'instanton' or 'skyrmion' scenarios. The first moments of the C–odd distributions $\Delta u^-, \Delta d^-$ can be determined at the level of few percent, while Δs^- could only be measured at the 10% level. This would be sufficient to test for instrinsic strangeness, and distinguish between skyrmion and instanton scenarios.

The determination of the shapes of the distributions is severely limited by the uncertainty on the shape of the gluon distribution. It turns out that $\Delta u(x)$ and $\Delta d(x)$ can only be measured with a precision around 15-20%, while no significant shape information can be obtained for $\Delta s(x)$.

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