Hadron Physics at a Neutrino Factory

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Abstract

We review the way intense neutrino beams at the front–end of a muon storage ring can be used to probe the structure of hadrons. Specifically, we discuss how the polarized and unpolarized flavor structure of the nucleon can be disentangled in inclusive deep-inelastic scattering, and how less inclusive measurements can shed light on various aspects of hadron structure such as fragmentation functions or generalized parton distributions.

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We review the way intense neutrino beams at the front-end of a muon storage ring can be used to probe the structure of hadrons. Specifically, we discuss how the polarized and unpolarized flavor structure of the nucleon can be disentangled in inclusive deep-inelastic scattering, and how less inclusive measurements can shed light on various aspects of hadron structure such as fragmentation functions or generalized parton distributions.

1. PHYSICS AT A NEUTRINO FACTORY

The use of a muon storage ring as an intense source of neutrinos has attracted renewed attention: it is a natural stepping stone toward a muon collider, and it would offer a wealth of opportunities for doing physics both of neutrinos (long baseline), and with neutrinos (front-end). Whereas the physics of neutrino oscillations, and in particular the possibility of discovering CP violation in the neutrino sector provide some of the strongest motivations for a neutrino factory, a sizable part of the physics program at such a facility should be devoted to the use of the neutrino beam as a probe of matter.

Front-end physics at a neutrino factory is based on the realization that, because of the flavor and spin structure of the coupling of neutrinos to weak currents, a neutrino beam has a greater physics potential than conventional electron or muon beams, and it can be used to perform tests of unsurpassed precision of the standard model, and as a probe of hadron structure of unique sensitivity.

Here we will briefly review the potential of neutrino beams as probes of matter. First, we will review deep-inelastic scattering (DIS) with neutrino beams, and show that it can be used to sort out the flavor structure of parton distributions of the nucleon, both polarized and unpolarized. Then, we will consider increasingly less inclusive measurements, and see how they can be used to shed light on various other aspects of hadron structure, such as fragmentation functions and generalized parton distributions.

The results discussed here are based on a recent detailed quantitative study performed by a CERN working group [1]; quantitative estimates given here are taken from there unless otherwise stated, and are based on the ‘CERN scenario’ [2] for a neutrino factory: specifically, a 50 GeV $\mu$ beam, with $10^{20}$ muon decays per year along a 100 m straight section. For other studies on the physics potential of neutrino factories see Ref. [3]; a recent status report on the neutrino factory/muon collider project is in Ref. [4].
2. DEEP-INELASTIC SCATTERING WITH PARITY VIOLATION

Inclusive DIS is the standard way of accessing the parton content of hadrons. The use of neutrino beams allows one to study DIS mediated by the weak, rather than electromagnetic interaction. The neutrino-nucleon deep-inelastic cross section for charged–current interactions, up to corrections suppressed by powers of $m_p^2/Q^2$ is given by

$$\frac{d^2\sigma^{\lambda_p\lambda_{\ell}}(x, y, Q^2)}{dx dy} = \frac{G_F^2}{2\pi(1 + Q^2/m_W^2)^2} \frac{Q^2}{x y} \left\{ \begin{array}{c} -\lambda_{\ell} y \left(1 - \frac{y}{2}\right) x F_3(x, Q^2) \\
(1 - y) F_2(x, Q^2) + y^2 x F_1(x, Q^2) \\
-2 \lambda_p \left(1 - y\right) x g_4(x, Q^2) - y^2 x g_5(x, Q^2) \end{array} \right\} ,$$

where $\lambda$ are the lepton and proton helicities (assuming longitudinal proton polarization), and the kinematic variables are $y = \frac{p_{\ell} \cdot q}{p_{\ell} \cdot k}$ (lepton fractional energy loss), $x = \frac{Q^2}{2p_{\ell} q}$ (Bjorken $x$). The neutral–current cross–section is found from Eq. (1) by letting $m_W \to m_Z$ and multiplying by an overall factor $\left[ \frac{1}{2} (g_V - \lambda_{\ell} g_A) \right]^2$.

The advantage of $W$ and $Z$-mediated DIS over conventional $\gamma^*\text{DIS}$ is clear when inspecting the parton content of the polarized and unpolarized structure functions $F_i$ and $g_i$. Up to $O(\alpha_s)$ corrections, in terms of the unpolarized and polarized quark distribution for the $i$–th flavor $q_i \equiv q_i^{\uparrow\uparrow} + q_i^{\uparrow\downarrow}$ and $\Delta q_i \equiv q_i^{\uparrow\uparrow} - q_i^{\uparrow\downarrow}$

$$\begin{align*}
\text{NC} & \quad F_1^Z = \frac{1}{2} \sum_i e_i^2 (g_i + \bar{q}_i) \\
\text{NC} & \quad F_1^W = \frac{1}{2} \sum_i (g_V^i + g_A^i) (q_i + \bar{q}_i) \\
\text{NC} & \quad F_2^Z = 2 \sum_i (g_V^i g_A^i) (q_i + \bar{q}_i) \\
\text{NC} & \quad F_2^W = \bar{u} + d + s + \bar{c} \\
\text{CC} & \quad F_3^{W^+} = \bar{u} - d - s + \bar{c} \\
\text{CC} & \quad F_3^{W^+}/2 = \bar{u} - d - s + \bar{c} \\
F_2 & = 2 x F_1 \\
g_4 & = 2 x g_5
\end{align*}$$

Here $e_i$ are the electric charges and $(g_V)_i$, $(g_A)_i$ are the weak charges of the $i$–th quark flavor. If $W^+ \to W^-$ (incoming $\bar{\nu}$ beam), then $u \leftrightarrow d$, $c \leftrightarrow s$. The structure functions $F_3$, $g_2$, and $g_4$ for the ‘wrong’ helicities ($\lambda_{\ell} = \lambda_p = 1$) are obtained from those for the ‘right’ helicities by exchanging light and heavy quark flavors.
Figure 2. Percentage errors (left, solid) and correlation coefficients (right) of parton distributions at a \( \nu \) factory compared to present–day errors (left, dashed).

\( g_4 \) and \( g_5 \) are parity-violating, and therefore not accessible in virtual photon scattering. Of course, beyond leading order in the strong coupling each quark or antiquark flavor’s contribution receives \( O(\alpha_s) \) corrections proportional to itself and to all other quark, antiquark and gluon distributions. The gluon correction is flavor-blind, and thus decouples from the parity-violating structure functions \( F_3, g_4 \) and \( g_5 \).

Hence, thanks to the weak couplings, more independent linear combination of individual quark and antiquark distributions are accessible. A further advantage of a neutrino factory follows from the fact that the neutrino beam has a broad-band energy spectrum (Fig. 1). Because \( y = Q^2/(2xm_\nu E_\nu) \), at fixed \( x \) and \( Q^2 \), \( y \) only varies with the beam energy. Hence, at a neutrino factory it is possible to disentangle the individual structure functions which make up the cross section Eq. (1) by measuring the neutrino energy on an event-by-event basis, and then fitting the \( y \) dependence of the data for fixed \( x \) and \( Q^2 \) (Fig. 1).

2.1. Unpolarized DIS and precision tests of the standard model

Unpolarized parton distributions are a necessary ingredient in the computation of any collider process. However, only the up, down and gluon distributions can be determined in a reasonably accurate way from present-day DIS data. Also, only the combination \( q_i + \bar{q}_i \) can be extracted from \( \gamma^* \)-mediated inclusive DIS. Some information on strangeness can be extracted from neutrino data, while some less–inclusive observables (such as \( W \) production, or Drell–Yan) provide some constraints on the relative size of the \( q \) and \( \bar{q} \) distributions, but the results are at best semi–quantitative (see Fig. 2).

Thanks to the availability of more independent combinations of parton distributions, full flavor separation would be possible at a neutrino factory. In Fig. 2 error estimates on individual partons at a neutrino factory are compared to the extant knowledge. Note that no current errors on strange and antiquark distributions are given, since the present results largely depend on theoretical prejudice. In Fig. 2 we further show that the point–by–point correlation of individual distributions determined at a neutrino factory is uniformly quite
low, indicating that a model–independent flavor and antilabor separation is possible to 10%–20% accuracy in most of the accessible kinematic range.

Such detailed knowledge of the flavor content of the nucleon, besides providing interesting clues on the nucleon structure, is crucial in extracting information on possible new physics signal from experimental data. For example, recently a $\sim 3\sigma$ discrepancy has been found between the determination of the Weinberg angle from the total $\nu$ DIS cross section [9] and the best fit standard model prediction. However, the most likely explanation of the effect [8] is a difference in shape between $\bar{s}$ and $s$ distributions, which was disregarded in the analysis of Ref. [9]. This $s - \bar{s}$ difference is compatible with current uncertainties, and favored by the analysis of Ref. [7], but essentially impossible to determine accurately with present-day data. This kind of situation is bound to become increasingly more common as subtle new physics effects will have to be disentangled from the huge standard background at future hadron colliders. It is unlikely that any other hadron physics facility (such as, for instance, the planned electron-ion collider [10]) could be competitive with a neutrino factory for flavor and quark-antiquark separation, and reach the level of accuracy of Fig. 2.

2.2. Polarized DIS and the proton spin puzzle

Polarized DIS has recently attracted considerable attention [11] because of the unexpected smallness of the proton’s singlet axial charge $a_0$. In the naive parton model the singlet axial charge is the fraction of the nucleon spin which is carried by quarks. The Zweig rule predicts that it should be approximately equal to the octet axial charge $a_8$, which differs from it because of the strange contribution, expected to be small in a nucleon. The octet charge can be determined using SU(3) from baryon $\beta$–decay constants: $a_8 = 0.6 \pm 30\%$, so the Zweig rule leads to expect that the quark spin fraction is around 60%. However, the experimental value is compatible with zero.

Clearly, this result points to a peculiar role of strangeness in the nucleon, but the issue is made more subtle by the inclusion of QCD corrections. Indeed, beyond leading order the axial charge is given by [12]

$$a_0 = \Delta \Sigma - \frac{n_f \alpha_s}{2\pi} \Delta G,$$

where $\Delta \Sigma = \sum_i (\Delta q_i + \Delta \bar{q}_i)$ is the scale–invariant quark spin fraction, and $\Delta G$ is the gluon spin fraction. The latter, due to the axial anomaly, gives an effectively leading–order contribution to $a_0$ Eq. (2). On the other hand, gluons decouple from the octet charge $a_8$. So, a first possibility is that gluons are responsible for the difference: $\Delta G$ is large enough that the quark spin $\Delta \Sigma \approx a_8$ even though $a_0 << a_8$. (‘anomaly’ scenario). A different option (‘instanton’ scenario [13]) is that $\Delta \Sigma << a_8$ because of a large contribution from sea quarks $(\Delta q_i^{sea} = \Delta \bar{q}_i^{sea})$ whose polarization is anticorrelated to that of valence quarks, possibly because of ‘instanton’ QCD vacuum configurations. Yet another possibility (‘skyrmion’ scenario [14]) is that $\Delta \Sigma << a_8$ is small because of a large contribution from ‘valence’ strange quarks $|\Delta s| >> |\Delta \bar{s}|$.

At present, flavor separation is only possible in the isotriplet sector, and only the total quark and gluon spin fractions can be extracted from NC DIS data [17], and then with modest accuracy: $\Delta G(1,1\,\text{GeV}^2) = 0.8 \pm 0.2$, $\Delta \Sigma(1) = 0.38 \pm 0.03$. It is of course impossible to polarize the kind of targets which are required for present–day neutrino DIS
experiments, so little information on strangeness and no information at all on the quark–antiquark separation is available in the polarized case. At a neutrino factory, significant rates could be achieved with small targets [15]: with a detector radius of 50 cm, 100 m length, the structure functions $g_1$, $g_5$ could be independently measured to an accuracy which is about one order of magnitude better than that with which $g_1$ is determined in present charged lepton DIS experiments. On the basis of such data, the distinct scenarios could be well separated from each other [16]: for instance in an ‘instanton’ scenario \[ \Delta s - \bar{\Delta s} \mid (1, 1 \text{GeV}^2) = -0.007 \pm 0.007; \] while in a ‘skyrmion’ scenario one would observe \[ \Delta s - \bar{\Delta s} \mid (1, 1 \text{GeV}^2) = -0.106 \pm 0.008. \] In fact full flavor separation at the level of first moments would be possible. Again, the same result could be hardly achieved anywhere else, since forthcoming experiments are unlikely to determine $\Delta s$ and $\bar{\Delta s}$ better than current experiment determined the unpolarized $s$ and $\bar{s}$.

3. THE NEUTRINO FACTORY AS A CHARM FACTORY

Semi-inclusive experiments are a large fraction of the physics program of present-day electron scattering experiments such as COMPASS [18] and HERMES [19]. At a neutrino factory, semi-inclusive charm production would be copious and easy to detect, because of the pair of opposite-sign muons in the final state which characterize the charm decay. A precise determination of the unpolarized and polarized tagged charm structure functions would be possible, since

\[
F_{W+}^{1c}(x, Q^2) = |V_{cs}|^2 s(\xi, \mu_c^2) + |V_{cd}|^2 d(\xi, \mu_c^2); \\
g_{W+}^{1c}(x, Q^2) = |V_{cs}|^2 \Delta s(\xi, \mu_c^2) + |V_{cd}|^2 \Delta d(\xi, \mu_c^2).
\]

This would allow a precise direct determination of the strange distribution (see Fig. 3), though in the polarized case one should worry about possible large gluon corrections, similarly to Eq. (2). Also, one could perform accurate studies of deep-inelastic charm production close to threshold, which is theoretically quite interesting in perturbative QCD due to the simultaneous presence of two hard scales ($Q^2$ and $m_c$).

4. POLARIZED Λ PRODUCTION AND FRAGMENTATION FUNCTIONS

Semi-inclusive production of specific particles offers information on both parton distributions and fragmentation functions. An example is polarized Λ production: the Λ polarization can be determined from the angular distribution of its decay, and one can construct asymmetries which are directly sensitive to polarized fragmentation functions. The latter are currently poorly known, and can only be determined on the basis of theoretical assumptions [21]: e.g. that they are SU(3) flavor symmetric, or on the contrary that the octet combination is much larger than the singlet, in analogy to what happens for the proton spin fraction. Predictions for the asymmetry $P(\Lambda) = \frac{d\sigma^{\Lambda^+} - d\sigma^{\bar{\Lambda}^-}}{d\sigma^{\Lambda^+} + d\sigma^{\Lambda^-}}$ as a function of the momentum fraction $z$ carried by the fragmenting quark are shown in Fig. 4.
Figure 4. A polarization $P(\Lambda)$ at COMPASS (left, from Ref. [22]) or a $\nu$ factory (right) for unpolarized (0) or polarized ($\pm$) target or (COMPASS) beam, in a ‘proton spin’ (Sc. 2) or ‘SU(3) symmetric’ (Sc. 3) scenario for fragmentation functions.

for fragmentation functions based on different theoretical assumptions, and for $e^{-}$ DIS (COMPASS) or $\nu$ DIS. Just as for structure functions, the flavor dependence of $\nu$ couplings makes results with a $\nu$ beam significantly more sensitive to the flavor structure of the fragmenting hadron.

5. EXCLUSIVE PRODUCTION AND GENERALIZED PDFS

Hard QCD factorization can be generalized to several less inclusive processes by introducing generalized parton distributions [23] (GPD) $F(x, t, Q^2)$. These quantities interpolate between the usual nucleon form factor $G(t)$ (which is related to the first $x$–moment of $F$) and parton distribution $F(x)$ (related to the $t \to 0$ limit of $F$). An example of such process is exclusive $D_s$ production (Fig. 5). In the kinematic region where the virtuality $Q^2$ of the $W$ boson is large compared to the nucleon momentum transfer $t$ and all masses, the cross section for the process factorizes as

$$\frac{d\sigma}{dx_{Bj}dQ^2dt}(W^- + N \to D_s^- + N) = H \otimes \Phi_D \otimes F,$$

where $H$ is the cross–section for the underlying hard perturbative parton subprocess, $\Phi_D$ is the $D^-$ fragmentation function, and $F$ is the GPD. The estimated cross section for this process is $\sigma = 2.2 \times 10^{-5}$ pb. The CHORUS collaboration has observed one such event, but in the region $Q^2 \lesssim t \approx 1$ GeV$^2$. At a neutrino factory, one would observe $10^4$ event/yr, thus offering the possibility of a good determination of the GPD.

Figure 5: Two of the Feynman diagrams for hard exclusive $D_s$ production.
6. OUTLOOK

The focus of studies of the structure of hadrons is currently moving toward either precision measurements (e.g., for parton distributions) or rare processes (e.g., for generalized parton distributions). Both are well served by the peculiar features of a neutrino beam, namely the availability of a probe which depends both on spin and flavor. The physics potential of such a beam can only be exploited given high enough intensity. However, a high intensity neutrino beam opens the possibility to a class of measurements which are essentially impossible at any other facility. Even though the time scale for a neutrino factory is greater than ten years, it is unlikely that many relevant issues of hadron physics, such as the proton spin puzzle, will find a satisfactory experimental answer elsewhere.

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