Single-Spin Asymmetries in Semi-Inclusive Deep-Inelastic Scattering on a Transversely-Polarized Hydrogen Target

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The closer one can look at matter the more surprises it has to offer. Modern "microscopes" in forms of huge particle accelerators have revealed a rich substructure of what were thought to be basic building blocks of matter: protons and neutrons. Nowadays we have accepted the fact that these nucleons, the basic ingredients of nuclei, are made of even smaller, probably point-like partons: quarks and gluons. All the properties of a nucleon can be derived, in principle, from the underlying theory which describes this substructure: *Quantum Chromo-Dynamics* (QCD). In reality we are far from close to be able to calculate those properties from the basic principles of QCD but phenomenologically, it is possible to characterize the nucleon in terms of parton distribution functions (PDF's) that describe how often one will find partons in a certain state. These functions are usually given as functions of the Bjorken scaling variable x, which, in a frame where the nucleon is moving with infinite momentum, can be intrerpreted as the fraction of the nucleon's momentum carried by that parton. A large number of parameters of such a description need to be quantitatively determined in experiments.

One aspect of the structure of the nucleon deals with its *intrinsic* angular momentum or "spin", e.g., how do the partons contribute to this *intrinsic rotation* of the nucleon. The investigation of the nucleon's spin structure is the main task of the Hermes experiment at Desy. For this it uses the positron beam of Hera which scatters off a polarized nucleon target. In this scattering process an energetic virtual photon, the probe, gets emitted and interacts with the quarks inside the nucleon. The energy and momentum transfer is so large that the quark being struck is expelled from the nucleon. The nucleon thus breaks apart, which is one major difference between such a *deep inelastic scattering* (DIS) event and an elastic scattering event in which the nucleon stays intact. The various fragments of the nucleon then form new hadrons (particles which are made of quarks) until all the energy of the photon is used up. As the expelled quarks will usually carry most of the energy of the photon, one can look for the most energetic hadrons to obtain clues about those quarks. For instance, the positively charged *up* quark prefers to form a π^+ meson which itself contains an up quark. Similarly the negatively charged *down* quark most likely forms a π^- meson.

In order to study the spin structure of the nucleon, Hermes makes use of another "preference" in the particle world: the photon "selects" quarks with a certain spin direction. By reversing the spin of the nucleon and hence that of the quarks one can study the difference in the number of quarks with their spin aligned or anti-aligned to the spin of the nucleon. Hermes took data in such a configuration, i.e., with a longitudinally polarized nucleon target, during its first data taking period. More recently, it has been taking data with a transversely polarized proton target, i.e., perpendicular to the positron beam direction. This allows the extraction of the last unknown quark distribution function of the nucleon, the *transversity* distribution. It describes the difference in the probabilities to find quarks in a transversely polarized nucleon with their spin aligned to the spin of the nucleon and quarks with their spin anti-aligned.

In the framework of PDF's there are three fundamental quark distributions: the quark number density, which has been measured with extremely high precision at the Hera collider experiments, the helicity distribution, which as mentioned was the main topic of the first Hermes physics run, and the transversity distribution. The difference between the transversity distribution and the helicity distribution lies in the polarization of the nucleon: transverse in the case of the transversity distribution vs. longitudinal in the case of helicity distributions.

In absence of relativistic effects the transversity and helicity distributions would coincide. A difference in the two quantities would therefore be a measure of how much relativistic effects have to be considered in the description of the nucleon. A different aspect of such a measurement is the comparison with theory: transversity measurements are classic benchmarks for calculations using lattice gauge theory.

Yet there is more to explore. Using a transversely polarized target one can study more complex distribution functions. An extension of the classical description of the nucleon structure includes the effects of transverse momentum of quarks inside the nucleon. This allows the introduction of a new class of distribution functions: the distributions not only depend on the momentum fraction x carried by the quarks but also on their transverse momenta $p_\perp$. In fact, integrating over the transverse momentum those contributions to the scattering cross section will cancel out. The only remaining distributions are then the three afore-mentioned PDF's.

A $p_\perp$-dependent distribution function which is of particular interest is the so-called Sivers distribution function. It describes the distribution of unpolarized quarks in a transversely polarized nucleon. There is large interest in the Sivers function as it may lead to an understanding of results from hadron-hadron collision experiments, and even more because of its behaviour under a transformation called time reversal. Simply speaking time reversal describes how processes would behave if time would go backwards. Clearly, burning a piece of wood is not symmetric under time reversal; it is, however, difficult to detect time reversal in a situation where a ball is bouncing off the ground (neglecting friction). QCD is – like the theory describing the bouncing of the ball – a the-

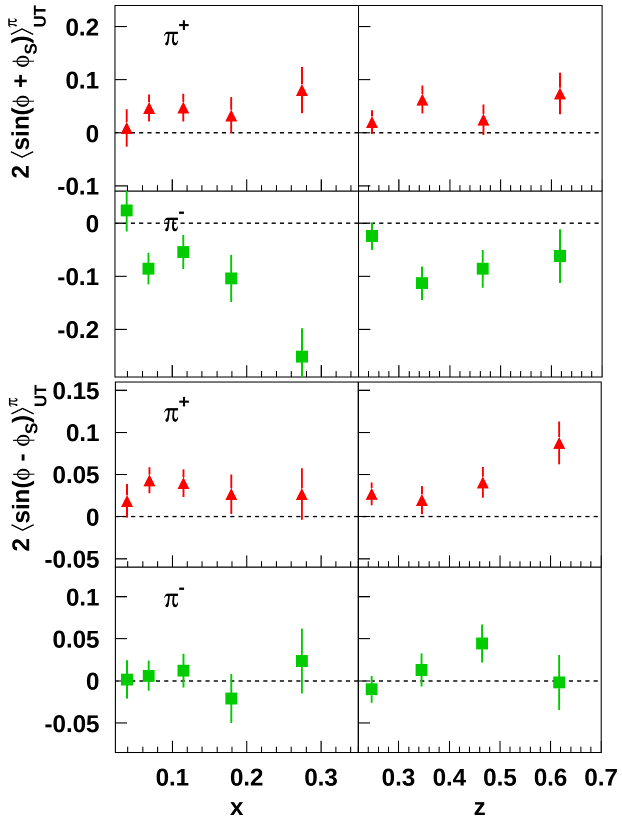

FIG. 1: Analyzing powers for the Collins (top) and Sivers effect for charged pions as functions of x and z.

ory symmetric or "even" under time reversal. However, the Sivers function is "odd" and changes its sign under time reversal. This strange behavior – so it was believed for a long time – forbids its existence. Only recently it became clear that there exist "loopholes" in the theory which permit such odd distribution functions. Therefore it is even more interesting to know whether these considerations are just *Gedankenexperiments* or whether the Sivers function does indeed exist! A side aspect of the above considerations is that one needs orbital angular momentum inside the nucleon to explain a non-vanishing Sivers function. With a transversely polarized target one thus is not only able to study the spin of the quarks but also their orbital angular momentum – one major contribution to the *spin puzzle* of the nucleon.[1]

The transversity measurement and the measurement of the Sivers function have one thing in common: both are based on "semi-inclusive" DIS events in which, in addition to the scattered positron, at least one of the produced hadrons is detected. By reversing the spin direction of the nucleon one can then study the dependence of the preferred direction of the outgoing hadron on the nucleon's spin direction.

After its first year of taking data with a transversely polarized target, HERMES has observed enough scattering events to have a first look at those angular dependencies. In Fig. 1 one can see the so-called analyzing powers for both the Sivers effect and the Collins effect (which is related to transversity) for the two charged π mesons. The analyzing power is a measure of how much the particle prefers to go into a certain direction. It lies between -1 ("always go into the opposite direction") and +1 ("always go in that direction"). They are plotted as functions of x, the proton's momentum fraction carried by the struck quark, and vs z, the virtual photon's energy fraction carried by the observed π meson.

A striking result is the comparably large signal for the π^- Collins effect. It came as quite a surprise since one had expected a behavior similar to what has been seen using a longitudinally polarized target namely a signal which is larger in size for the π^+ than for the π^-. This will have important consequences for an understanding of how the hadron is formed from the struck quark. However, at the moment the statistical significance is not good enough to make definite statements about the exact behavior of the involved functions.

An equally interesting result is the observation that for the π^+ the signal for the Sivers function is not zero! This is the first confirmation that the Sivers function exist and an evidence for non-vanishing time reversal odd parton distribution functions.

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[1] There remains a mystery up to today about what makes the spin of the nucleon. It is only clear that the contribution of the quark spin to the spin of the nucleon is small. Other contributions like the orbital angular momentum of quarks have not been measured yet.