Observation of the Naive-T-odd Sivers Effect in Deep-Inelastic Scattering

The HERMES Collaboration

The exploration of the tiniest building blocks of matter is the core task of the experiments performed at DESY with the HERA accelerator. We have known since about a century that atoms are made of electrons and nuclei. Inside the nuclei we can find protons and neutrons (called *nucleons*). Since the late Sixties, we have been able to peer into the nucleons by piercing them with ultrafast electrons, through a process called *deep-inelastic scattering*. We discovered that nucleons are made of even smaller particles, quarks and gluons, collectively called *partons*. In deep-inelastic scattering, the electrons hit hard the quarks inside the nucleon; the electron bounces off in a way that depends on the distribution of quarks in the nucleon; the struck quark is kicked out of the proton and the proton itself is blown to smithereens.

During the last forty years, tremendous progress in the technology employed in deep-inelastic scattering experiments, and in the sophistication of the theoretical interpretation of the experimental results has been achieved. For instance, early experiments were able to measure only the scattered electrons, thus accessing only part of the information exposed by the scattering process. Nowadays, detectors placed around the collision point can also identify many of the smithereens produced in the collision. This kind of experiment (called *semi-inclusive deep-inelastic scattering*) essentially allow us to take multi-dimensional snapshots of the inner structure of the nucleons.

For sake of simplicity, we can imagine the nucleon as made of a bunch of partons, very tightly joint together. In a typical deep-inelastic scattering collision, the nucleon races fast in one direction to meet an electron coming in from the opposite direction. Each of the partons carries a fraction of the momentum of the nucleon, so that they all add up to make a prodigious total momentum. Nowadays, we know accurately how the total momentum is shared among the partons. Roughly speaking, for each parton species we are able to compile a histogram where we count how many partons carry a certain fraction of momentum. We can draw a "skyline" of the distribution of partons, which is taller if more partons carry a certain momentum. In this sense, we have a mono-dimensional picture of the nucleon *in momentum space*.

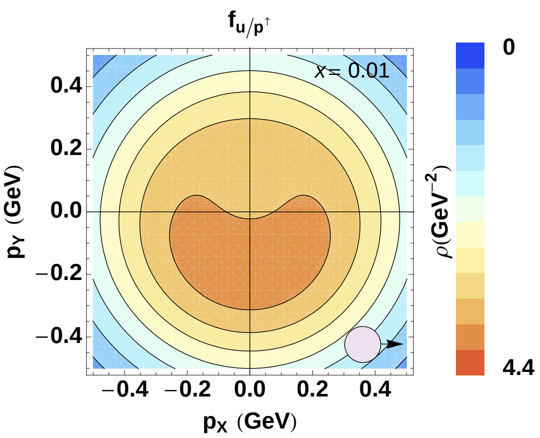

FIG. 1: Distortion of the up quark density due to the Sivers effect. The nucleon moves out of the sheet. Up quarks tend to have a downward momentum if the nucleon is polarized in the direction indicated by the small arrow in the left-bottom corner.

But the structure of the nucleon is much more intricate and fascinating than that. First of all, partons do not move all in the same direction in an orderly manner. They wander around also in directions transverse to the nucleon's path. We would like to have a picture of the nucleon in all directions: not just a skyline, but a real multi-dimensional landscape. We want to know what is the shape of the nucleon in momentum space: does it look like pancake, or a bagel, or something weirder?

Secondly, nucleons have *spin*, which roughly means that the partons inside the nucleon collectively spin or revolve to generate the total spin of the nucleon. One of our goals is to pin down how much of the proton spin is built up by the partonic spins or their orbital angular momentum. There can be correlations of all kinds between the spin of the nucleon, the spin of the partons and the momentum of the partons. Each kind of correlation can teach us something new about the way partons are organized inside the nucleon and can help us estimating how large is the contribution of partonic angular momentum to the spin of the nucleon.

The present article presents a measurement related to a specific correlation between the spin of the nucleon and the momentum of the partons. This kind of correlation is called *Sivers function*. Suppose the nucleon is polarized to the right and moving toward you: a positive Sivers function means that the partons are more likely to move downward rather than upward (see Fig. 1). Grasping the nature of this kind of correlations can be mindboggling... that's why we like them!

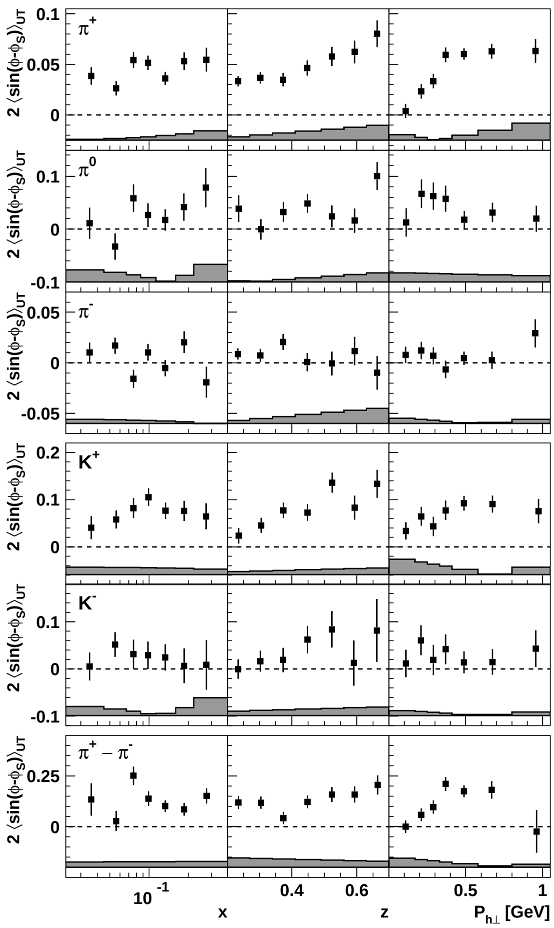

FIG. 2: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry (as denoted in the panels) as functions of x, z, or $P_{h\perp}$.

In a concrete experiment it is not possible to directly observe how the partons are moving inside the nucleon. Rather, we see the effect of the primordial partonic motion through the distribution of the debris after a deep-inelastic collision. We keep the nucleon polarized in, e.g., the upward direction, we point the beam of electrons into it and we look at distortions in the ensuing shower of particles. If we notice that some particles prefer to go to the left of the plane formed by the proton spin and the beam direction, we conclude that a nonzero Sivers function is involved.

The HERMES experiment is one of the few experiments worldwide where the Sivers effect can be measured, because it was designed to perform semi-inclusive deep-inelastic scattering off nuclear-polarized targets. A few years ago, HERMES presented the first-ever measurement of the Sivers effect. The results reported in this article are shown in Fig. 2. We dramatically improved the statistical precision on the measurement for charged pions (π^+ and π^- panels), and for the first time we present the Sivers asymmetries for neutral pions (π^0), kaons (K^+ and K^-), and the pion-difference.

The qualitative features of the asymmetries measured by our experiment are still to be fully understood. For instance, it is a bit unexpected to see a clearly nonzero asymmetry for the positively charged pions (π^+) and basically no asymmetry for the negatively charged ones (π^-). It is also unexpected to see the positive kaons (K^+) asymmetry being even larger than the positive pions.

Another cool property of the Sivers function is that it is expected to change according to the way we "look at it." If we use deep inelastic scattering (a beam of electrons shot against a nucleon target) the Sivers function has a certain sign, i.e., the quarks are distorted in the way depicted in Fig. 1. But if we use Drell–Yan scattering (shooting a beam of nucleons against a nucleon target), the Sivers effect should change sign. This peculiar behavior can be understood as the effect of looking at the nucleon with different lenses or filters. If this QCD expectation is confirmed, it will mark a great success of the theoretical framework we use to interpret these experiments.