Azimuthal distributions of charged hadrons, pions, and kaons produced in deep-inelastic scattering off unpolarized protons and deuterons

The Hermes Collaboration

Understanding the internal structure of matter is one of the most fascinating challenges in the history of humankind. In the last century significant progress has been made in the investigation of the fundamental constituents of matter. According to our present understanding, all ordinary matter is built from a small number of basic building blocks, e.g., electrons and quarks. The quarks are confined inside protons and neutrons, which, surrounded by electrons, form the atoms of all matter that we encounter in every day's life. To study the characteristics of electrons and nucleons (protons and neutrons), they have been kicked out of their bound states, the atoms, and studied as independent objects. To study how quarks behave and interact, the situation is more complex, as it appear not to be possible to isolate a single quark. The only way to access them is to study their bound states, the nucleons, and see how they react and interact in different situations.

One powerful tool to investigate the internal nucleon structure is deep-inelastic scattering (DIS), i.e., scattering of electrons off nucleons with large momentum transfer. In this reaction, the electrons do not interact with the nucleon as a whole, but have sufficient energy to enter the nucleon and interact with a single quark. The struck quark is pushed out of the nucleon, but, as it cannot exist in isolation, new quark-antiquark pairs are created and join the struck quark to form new particles called hadrons. This process is called fragmentation.

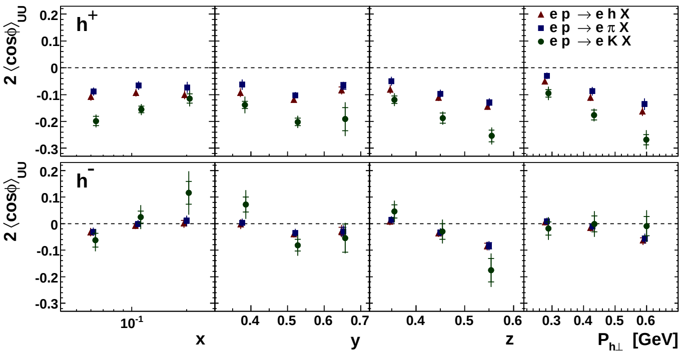

FIG. 1: $\cos\phi$ amplitudes from a hydrogen target for positive (upper panels) and negative (lower panels) unidentified hadrons (triangles), pions (squares) and kaons (circles).

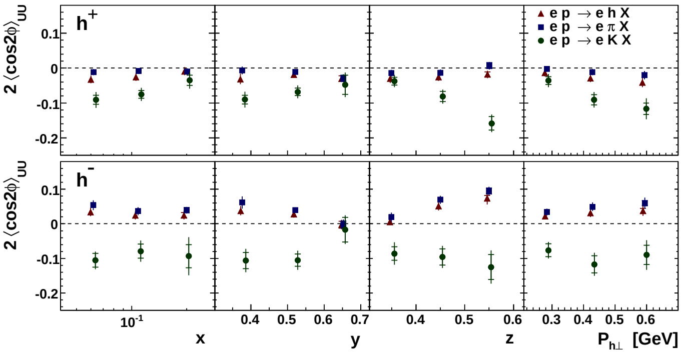

FIG. 2: $\cos 2\phi$ amplitudes from a hydrogen target for positive (upper panels) and negative (lower panels) hadrons (triangles), pions (squares) and kaons (circles)

By observing the reaction products of DIS it is possible to access two important quark features: how they are distributed within nucleons, (how many quarks of each type, i.e. flavor, are there? how do they interact?) and how they fragment into new particles. In the past 50 years physicists have answered these questions in some extent, and now we know how many flavors of quarks exist, their longitudinal momentum distribution inside nucleons, i.e., momenta along the nucleon momentum direction, their longitudinal polarization, and the probability for a quark with a particular flavor to fragment into different hadrons. Until very recently, the degrees of freedom which are transverse to the nucleon direction of motion, for instance the quark transverse momenta or transverse spins, were neglected. Indeed, they are much smaller than the corresponding longitudinal components, and it was believed that their effects in quark distributions or fragmentation should be small as well. Only recently physicists started to seriously ask whether quark transverse momenta or transverse spin may in fact generate measurable effects. They found that such effect are not only measurable, but can be large. An intense theoretical effort in the last few years has built a number of functions that describe the internal nucleon structure and the quark fragmentation, that depend on these additional quark kinematic variables. These functions are called transverse momentum dependent distribution functions (TMDs). TMDs are known theoretically, but depend on a number of parameters, some of which are difficult to access experimentally and thus are poorly constrained, or not measured at all, such as the average quark transverse momenta and transverse polarizations. Currently, theoretical models of TMDs include educated guesses for these parameters, but measurements are needed (a) to confirm that nature behaves as the TMD framework suggests, and (b) to experimentally measure the parameters upon which TMDs depend.

In DIS experiments TMDs generate azimuthal distributions in the directions of the reaction products, i.e. the scattered lepton and produced hadrons. Different combinations of beam and target polarizations results in different azimuthal modulations of the outgoing hadron direction. In this paper the azimuthal modulations generated by unpolarized beam and target are presented, in particular $\cos\phi$ and a $\cos 2\phi$ modulations are presented here. The $\cos\phi$ modulation is directly related to the internal quark transverse momentum, while the $\cos 2\phi$ modulation is related to correlations between the quark transverse momenta and their transverse spin, a *spin-orbit correlation*. As different hadrons are generated at different efficiencies by different quark flavors, the differences observed for the modulations extracted for the various particle types, as shown in Figs. 1 and 2, can provide informations about the transverse momentum and transverse spin of the different quark flavors.

This is the first measurement of its kind to include both the $\cos\phi$ and $\cos 2\phi$ modulations for both electrical charges of two hadron flavors (pions and kaons), as well as unidentified hadrons. This measurement has been extracted from electron scattering off both hydrogen and deuterium targets, which have different quark compositions and further help to disentangle the flavor dependence of TMDs. As such, this unprecedent complete picture allows for some tentative observations, dependent on the existing TMD framework, about the nature of different TMDs. For example, this data suggest that the two lightest quark flavors, *up* and *down*, have similar spin-orbit correlations, while for the *strange* quark these correlations appear to be larger.

This data will help to push forward the TMD description of the internal structure of the nucleon by providing a test bench for previous assumptions and ample data set on which to constrain models.