Effects of transversity in deep-inelastic scattering by polarized protons

The HERMES Collaboration

Can one distinguish quarks that possess a preferred spin orientation, i.e., polarization, from quarks without polarization merely by looking at the hadronization of these quarks into spin-less hadrons? Yes – so it was conjectured in a seminal publication by J.C. Collins when he introduced the Collins effect, a preference of the final-state hadron to move perpendicular to both the momentum and the polarization directions of the hadronizing quark (c.f. Fig. 1). Yes – so it was reported some five years ago by the HERMES Collaboration and confirmed by the BELLE Collaboration later on. But why would this be so interesting beyond the general question of how quarks form hadrons in the fragmentation/hadronization process? The answer to this dates back even further.

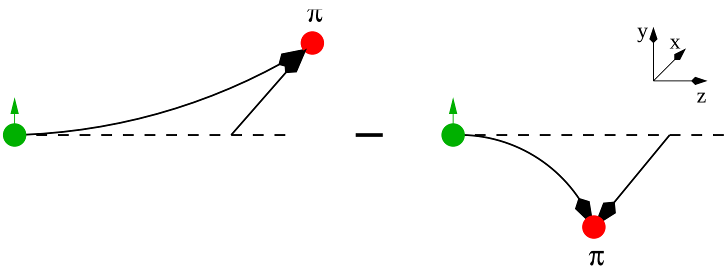

FIG. 1: Illustration of the Collins effect, *the preference of a hadron, e.g., a π meson, emerging in the fragmentation process of a transversely polarized quark to go either to the right or left in the direction perpendicular to the spin of the hadronizing quark.*

Physicists have striven for a simple explanation of the universe for centuries. In that quest they found smaller and smaller building blocks that were the ingredients of what makes matter. At some points atoms were believed to be the basic building blocks until it was found that they themselves consist of electrons surrounding the atom's cores, the nuclei. Even nuclei were not basic building blocks: protons and neutrons (categorized as nucleons) assembled to the various nuclei. Moreover, nucleons are compound structures of even tinier objects—quarks and gluons—which are believed to be elementary particles. They are so difficult to study that still today we know little about how they conspire to form what we know so well as nucleons. But what does the Collins effect have to do with all of this? In the investigation of the nucleon structure we would like to know not only what are the constituents of the nucleon, but also how the constituent's spin depends on the polarization of the nucleon, and the Collins effect gives us the rare opportunity to explore *transverse* polarization of quarks in the nucleon.

Quarks in a nucleon are confined to a tiny space with a diameter of about 1 fm, that's about 1/1,000,000,000,000$^{\text{th}}$ of a millimeter. They move around quickly and, as they possess spin, they can be polarized. In order to bring order to this myriad of possible states, certain structures, i.e., correlations between the momentum and the spin directions of the quarks, were introduced. In total, eight of such structures need to be introduced, nowadays categorized as transverse-momentum-dependent quark distributions (TMDs). That's for the theory, in praxis we would also like to measure these TMDs, but there the trouble begins. While it appears not so difficult to constrain the momenta of quarks, the spin direction can only be measured via some form of polarimetry. Longitudinal polarization, i.e., polarization along the momentum direction, can be probed with a spin-1 photon, as angular-momentum conservation dictates that in a head-on collision a photon with certain helicity can couple to quarks with the same helicity only. But how about transverse polarization? Here, as outlined above, the Collins effect comes in rather handy as it provides the necessary sensitivity to transverse quark polarization via the left-right asymmetry in the momentum distribution of the outgoing hadron. As such the previous HERMES measurement of the Collins effect in deep-inelastic scattering of positrons from transversely polarized protons not only demonstrated the existence of a non-zero Collins function but also the existence of transversely polarized quarks in a transversely polarized proton. (The distribution of such quarks is commonly denoted as *transversity*.)

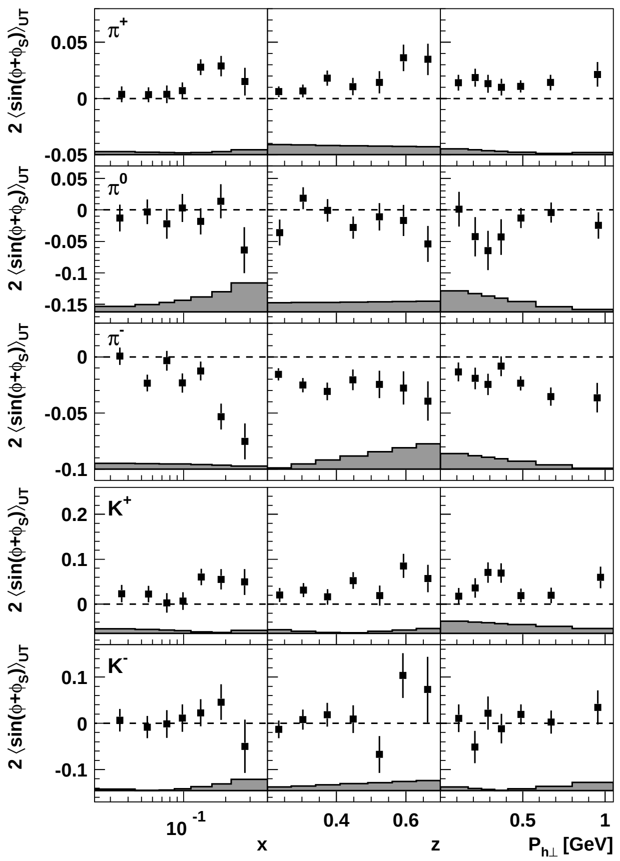

FIG. 2: Collins amplitudes for pions and charged kaons (as labelled) as functions of the fraction of the proton momentum, x, the fraction of the virtual-photon energy carried by the hadron detected, z, or the hadron's momentum component transverse to the direction of the virtual photon, $P_{h\perp}$.

In this paper, all available HERMES data on transversely polarized protons are reported on. This allows not only a considerably more precise measurement of the Collins effect for charged pions (compared to the previous measurement) but also, for the first time, for the neutral pion and for charged kaons. The Collins amplitudes (the measure of how strong is the left-right preference in the momentum direction of the outgoing hadron) are found to be non-zero for charged pions and the positively charged kaon whilst compatible with zero for the other two mesons. A striking feature of these data is the opposite sign of the amplitudes for negative vs. positive pions. This means that negative pions prefer to fly into the opposite direction to the one for positive pions. Not only that, the magnitude of the Collins amplitude for negative pions is even bigger than the one for positive pions. The preliminary version of these results, in combination with data from the BELLE and COMPASS collaborations, allowed for a very first extraction of transversity for u and d quarks. From that, but also already from the charged-pion results alone, we now know that quarks in a transversely polarized proton not only can possess transverse polarization, but also conclude that when a certain quark fragments into a pion then this pion tends to go to the left of the quark's spin when such quark is also a constituent, i.e., *valence* quark, in this pion. If it is not a valence quark then the pion prefers to go to the right side. While this behavior can qualitatively be explained in certain hadronization models, the full complexity of this results requires further investigations.

Another tantalizing aspect of these data are the results for kaons. While negatively charged kaons show no left-right preference at all, positive kaons have an even stronger preference in their momentum direction than positive pions. In an apparently naive approach the amplitudes should be similar as the production of both the positive pion and kaon might be assumed to be dominated by scattering off u-quarks and the u-quark polarization inside transversely polarized protons is the same regardless of the meson produced. Hence, we need to look beyond these simple assumptions and explore all the ingredients for meson production in deep-inelastic scattering from transversely polarized nucleons. Undoubtably, all these data provide valuable input for this and, in general, in the quest of unravelling the spin-momentum structure of the nucleon.