Studying hadronization: broadening of the transverse momentum of π^+, π^-, and K^+ produced in a nuclear environment.

Hadronization is the process of forming a hadron (eg. proton, pion, kaon, ...) out of quarks. As of today, this process is not well understood because it takes place in an energy regime where it cannot be fully described by a particular theory. In order to better understand this and distinguish among existing theories describing hadronization, several experiments can be done.

One way of studying hadronization is to accelerate a point-like particle, such as an electron, and let it interact with a target that consists of quarks (eg. proton). If the momentum of the electron is high enough, it is able (with the exchange of a virtual photon) to interact with a single quark. This quark will then form a hadron due to what is known as (color-)confinement. If quarks move away from each other the (color) force-field that holds them together is "stretched", and more energy is stored until it becomes energetically cheaper to form a new quark anti-quark pair. In this way isolated quarks do not exist.

If a proton or Deuterium (D) is used as a target, the quark is immediately kicked out of the nucleon and hadronization happens in "vacuum". Another way of studying hadronization is to introduce a nuclear medium where the hadronization process gets "disturbed". During hadronization, interactions with the nuclear medium are possible. One can compare hadronization in the nucleus with that in vacuum and learn something about the time-scales of this process.

The HERMES experiment uses an accelerated electron/positron beam on a fixed target. The targets used are Deuterium (hadronization in vacuum) and He, Ne, Kr, and Xe (hadronization in nuclear medium). The HERMES beam-momentum is very well-suited for this study, because at these momenta, the length or time it takes for a quark to hadronize is on the same order of magnitude as the diameter of the nuclear targets used.

The hadronization process can be divided into three stages that involve the propagation and interaction of: (a) the initial struck quark (partonic stage), (b) the subsequently formed state where the quark picks up an anti-quark to form the so-called pre-hadron (color-neutralization stage), (c) the final produced hadron.

The time/length it takes to form the pre-hadron is called the *production time/length* and the time/length it takes to form the final state hadron is called the *formation time/length*.

One study done at HERMES involved looking at hadron yields. By dividing the hadron yields produced on a nuclear target by those produced on a Deuterium target, one can study hadronization. This observation is mainly sensitive to the formation time depending on where (inside or outside the target nucleus) the final-state hadron is formed. An additional study, the one presented in this paper, measures the difference in transverse momentum obtained by the detected hadron produced using a nuclear target and obtained by the detected hadron using a Deuterium target. The transverse momentum is in the direction perpendicular to the direction of momentum transfer to the struck quark. Additional transverse momentum of hadrons produced in a nuclear target (compared to vacuum) is expected, since the struck quark, the pre-hadron, and final-state hadron, can interact with the nuclear medium and so acquire additional transverse momentum. Recent theories suggest that this observation is the most direct way to probe the production time or that most of the additional transverse momentum is acquired in the partonic stage.

In Figure 1 the results are shown; $\Delta\langle p_t^2\rangle$ (or p_t-broadening) is the difference in transverse momentum squared of hadrons produced on a nuclear target with hadrons produced on a D target. p_t-broadening is plotted as a function of several kinematic variables: ν is the energy which is absorbed by the struck quark, Q^2 is the total (four-)momentum absorbed by the struck quark, x is the fraction of the total momentum of the nucleon carried by the struck quark, and z is fraction of the energy that is absorbed by the struck quark carried by the final state hadron.

p_t-broadening from light to heavier targets (He to Xe in Fig. 1), increases without saturation. This indicates that the pre-hadron is produced outside or at the surface of the nucleus (in the HERMES kinematics) and that p_t-broadening is sensitive to the partonic stage. p_t-broadening does not depend on ν, which confirms that the pre-hadron is formed outside the nucleus. As ν increases, the partonic stage lasts longer, which would cause an increase of p_t-broadening if the pre-hadron formation takes place inside the nucleus.

The comparison of the broadening values with the average transverse momentum values $\langle p_t^2\rangle$ of hadrons produced on D (top row in Fig. 1), leads to the conclusion that p_t-broadening adds up to 10% of the average transverse momentum.

In Fig. 1 it can be seen that p_t-broadening is constant as a function of z and vanishes for z close to 1. This is due to energy conservation: z equals 1 means that the produced hadron carries all of the energy that was absorbed by the struck quark. Therefore, the produced hadron could not have undergone multiple interactions because that would cause energy loss and a z smaller than 1.

Another interesting behavior is the p_t-broadening as a function of Q^2 (or x which is highly correlated to Q^2 due to the acceptance of the HERMES spectrometer). The rising p_t-broadening for increasing Q^2 is in agreement with some theories and not with others.

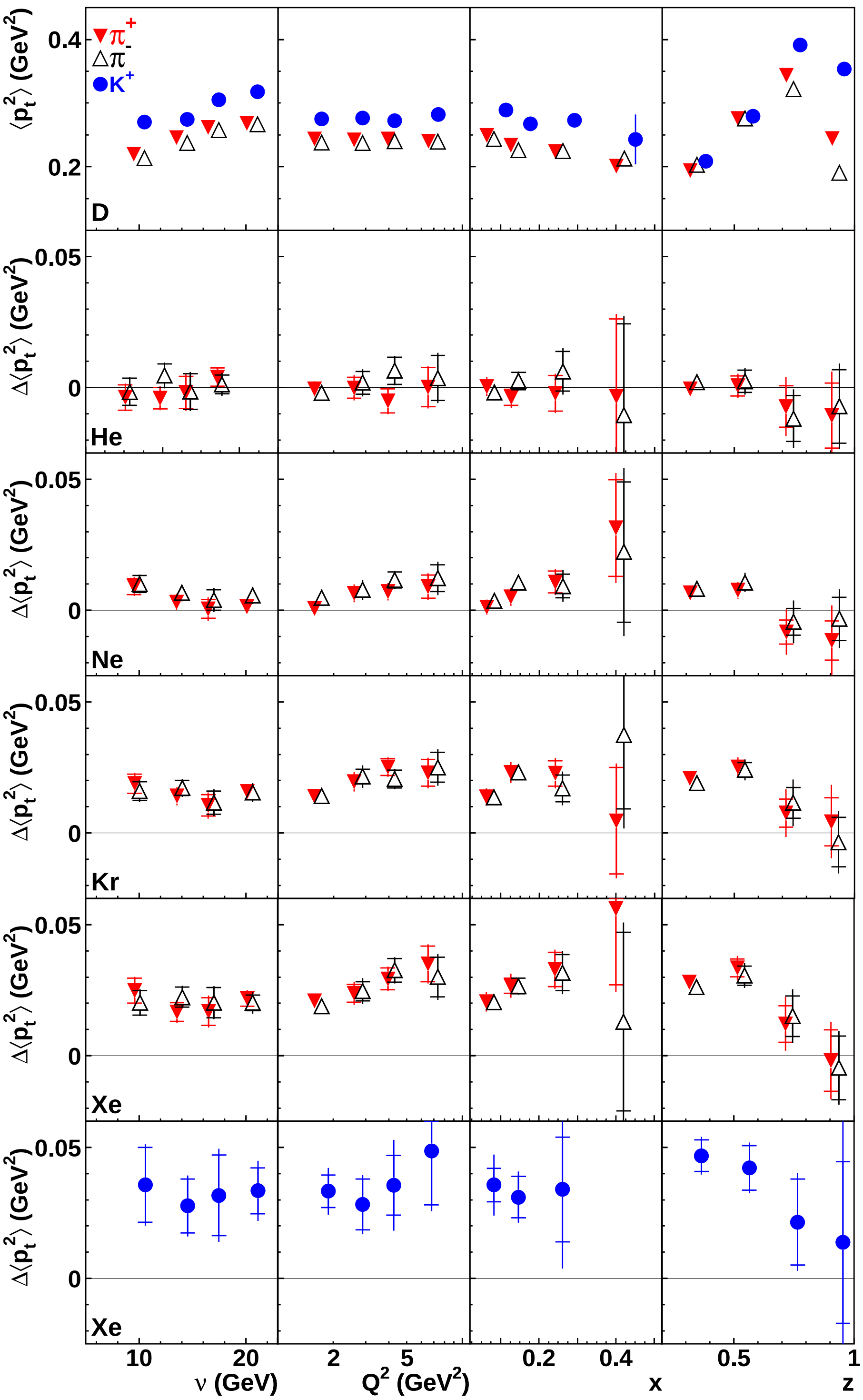

Figure 1: From left to right, the ν, Q^2, x, and z dependence of $\langle p_t^2 \rangle$ for D (top row) and p_t-broadening (remaining rows) for π^+ and π^- produced on the He, Ne, Kr, and Xe targets and for K^+ produced on the Xe target (bottom row). The inner error bars represent the statistical uncertainties; the total error bars represent the total uncertainty, evaluated as the sum in quadrature of statistical and systematic uncertainties.