Quark Propagation and Hadron Formation in the Nucleus

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Abstract. The results of Jefferson Lab experiment E02-104 which was performed in the CLAS detector at Thomas Jefferson National Accelerator Facility are presented. During the experiment, data on semi-inclusive production of hadrons in deep-inelastic scattering (DIS) of a lepton off nuclei were acquired. These data provide important information about the space-time development of in-medium hadronizaton as well as give an opportunity to investigate the fragmentation processes in the nuclear medium. Transverse momentum broadening and hadronic multiplicity ratios for positively charged pions were measured as multidimensional functions of kinematic variables from different nuclear targets.

Keywords: JLab, CLAS, hadronization, quark hadronization, hadron formation, deep inelastic scattering, DIS.
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In this paper are presented the preliminary results for data analysis of Jefferson Lab (JLab) experiment E02-104 [1,2]. The main goal of the experiment is to measure experimental observables necessary to study the propagation of quarks through the nuclear medium with the subsequent formation of the final state hadrons. For this purpose, a unique double-target system was designed [3]. The complete target system consisted of a liquid target and a solid target, which were in the beam simultaneously, located 4 cm apart. Carbon, aluminum, iron, tin, and lead were the solid target materials used during different run periods. Deuterium was chosen for the liquid target.

The main observables to measure are the *transverse momentum broadening* and the *hadronic multiplicity ratio* (*hadronic attenuation*) for the hadrons produced from semi-inclusive deep inelastic scattering (DIS) of a lepton off nuclei. *Transverse momentum broadening* is the difference between the average squared transverse momentum of final hadron for nucleus with mass *A* and a deuterium nucleus:

$$\Delta p_T^2 = \left\langle p_T^2 \right\rangle_A - \left\langle p_T^2 \right\rangle_{D_2}$$

Hadronic multiplicity ratio is the ratio of number of final hadrons produced on a nucleus with atomic number *A* to the same on deuterium normalized using DIS electrons:

$$R_M^h\left(z_h, \nu, Q^2, p_{T,}\phi\right) = \frac{\left\{\dfrac{N_h\left(z_h, \nu, Q^2, p_T, \phi\right)}{N_{e^-}^{DIS}\left(\nu, Q^2\right)}\right\}_A}{\left\{\dfrac{N_h\left(z_h, \nu, Q^2, p_T, \phi\right)}{N_{e^-}^{DIS}\left(\nu, Q^2\right)}\right\}_{D_2}}$$

where the arguments in the ratio are the common experimental variables used in DIS kinematics [1,2].

The acquired experimental data provide important information about the space-time development of in-medium hadronization. In the considered kinematic region Bjorken x is sufficiently large $x>0.1$ such that the lepton interacts incoherently with only one bound nucleon with a single photon exchange. Additionally this region is dominated by valence quarks, so that we can treat the DIS as electron-quark scattering. In this case, υ is simply the initial energy of the quark, and $z_h=E_h/\upsilon$ is to a good approximation the fraction of the struck quark's energy carried by the final hadron.

The primary processes affecting quarks propagating through nuclei are energy loss through gluon radiation and partonic elastic scattering inside the nucleus, as well as the hadronization process. The details of the hadronization process are not yet understood, although some aspects are known. According to the gluon bremsstrahlung model [4], the knocked out quark propagating through the medium radiates gluons which in turn might produce quark-antiquark pairs. This process continues until the colorless pre-hadronic state is produced. Afterwards the hadron formation starts, which ends with the final hadronic state. Thus the whole process can be divided into two distinct dynamical stages, each with characteristic time scale. The *production time* is the time during which the quark emitting gluons is deconfined. This period is signaled by medium-stimulated energy loss via gluon emission and production of the colorless pre-hadronic stage at the end. For investigation of that stage, observation of transverse momentum broadening is important. The *formation time* is the time required to form the color field of hadron, signaled by interactions with known hadron cross sections. No gluon emission occurs during that stage. For study of that process, the observation of hadron attenuation is important.

Experiments investigating this topic were also performed by the HERMES collaboration [5]. HERMES has published data for helium, nitrogen, neon, krypton and xenon targets, including fully identified hadrons in the final state. These high-quality data have stimulated a new wave of modeling from various points of view. All of the new models are able to describe the HERMES data in some measure, although they are based on somewhat different physical pictures. The different approaches can be listed: Baier, Dokshitzer, Mueller, Peigne, and Schiff (BDMPS) and quark energy loss [6], gluon bremsstrahlung model [4], “twist 4 pQCD model” [7], “BUU model” [8], “Arleo model” [9], rescaling model and two-time-scale model” [10], etc.

Compared to the HERMES experiment, the JLab 5 GeV experiment, while more limited in kinematic reach than the HERMES experiment, gives an opportunity to observe qualitatively new behavior due to the much higher JLab luminosity and the capacity for accommodating solid targets, thus probing the largest nuclei. Because the JLab data have two orders of magnitude more integrated luminosity, it is possible to bin the data in up to four kinematic variables while preserving good statistical accuracy. In addition to that, the Jlab experimental data provide an opportunity for definitive measurements of unprecedented precision for the value of Δp^2_T.

As mentioned above, the main goals are to measure the transverse momentum broadening and hadronic attenuation as a function of five different kinematical variables in 2, 3, and 4-fold kinematical bins. These kinematical variables are: $z_h=E_h/\upsilon$ is the fraction of struck quark’s energy carried by the hadron, Q^2 and υ are correspondingly the four-momentum and energy transferred by the electron, p^2_T is the hadron momentum transverse to the virtual photon direction squared, and ϕ is the azimuthal angle around the virtual photon direction of the electron-hadron scattering plane.

In Figure 1 the transverse momentum broadening dependence on nuclear size $A^{1/3}$. Measurements are performed in certain $z_{\pi+}$, Q^2, υ kinematic bins for positively charged pions for carbon, iron and lead as solid targets. This plot corresponds to only one of many available kinematic bins included in the data set.

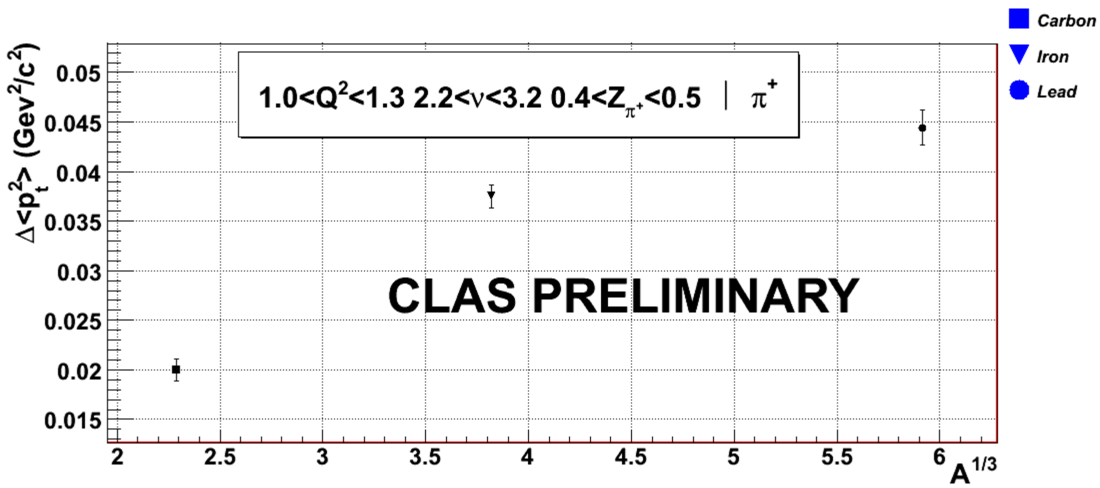

FIGURE 1. Transverse momentum broadening dependence on $A^{1/3}$ in a three-fold kinematical bin (see plot label).

In Figure 2 are presented sample plots of the hadronic multiplicity ratio dependence on $z_{\pi+}$, Q^2, υ and $p^2{}_T$ for positively charged pions for carbon, iron and lead marked correspondingly by squares, triangles and circles. The results presented are in certain kinematic bins and those are only a small fraction of all available data. The last of the four plots represents the so-called Cronin effect [11] which was first observed in heavy-ion and hadron-nucleus reactions. The $p^2{}_T$ distribution of the observed hadrons is expected to be broadened on a nuclear target compared to a deuterium target due to multiple scattering of the propagating quark with a small contribution from hadron elastic scattering. This effect is also observed in the HERMES data for the available nitrogen and krypton data [5].

The stringent constraints imposed by the new JLab data will soon clarify what the essential model ingredients are. In particular, it is crucial to establish the relative importance of the two processes of gluon bremsstrahlung and pre-hadron interactions in describing the kinematic and flavor dependencies of $R^h{}_M$, and to understand the role of quantum interference in these processes. At that point it will be feasible to fully analyze the data from the 5 GeV beam and from the 12 GeV upgrade experiment E12-06-117 [12], extracting hadron formation lengths from a variety of produced hadrons and constraining the mechanisms involved in their formation.

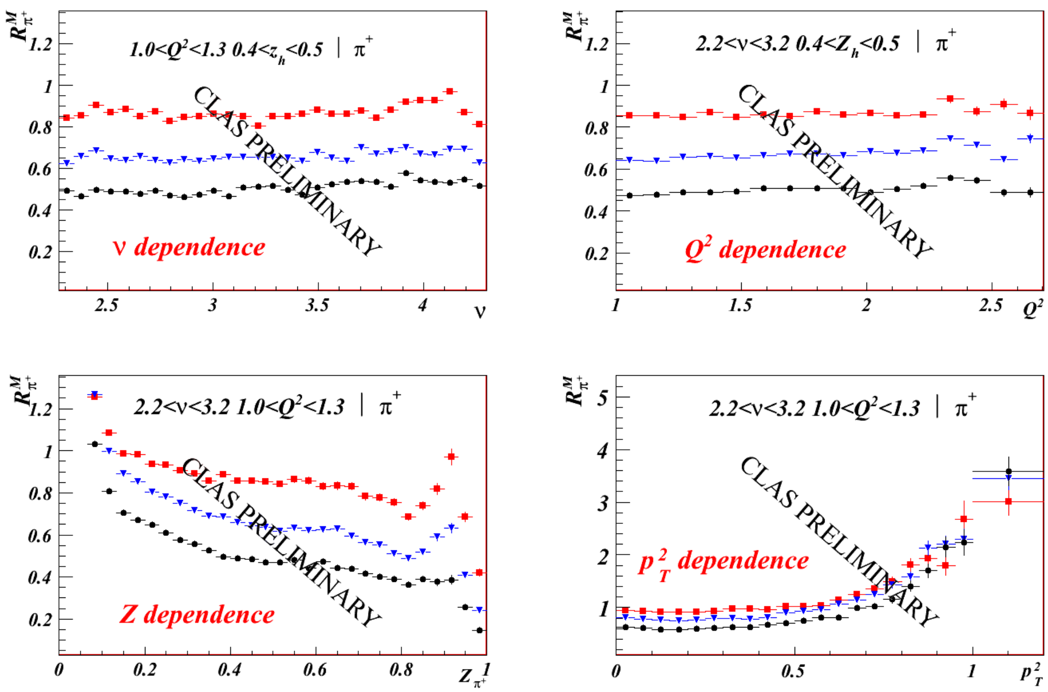

FIGURE 2. Hadronic multiplicity ratio dependence on z_{π^+}, Q^2, ν and $p^2{}_T$ in kinematical bins (see plot label) for positively charged pions in case of carbon (squares), iron (triangles) and lead (circles).

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