The Structure of the Building Blocks of the Universe

Extraction of unpolarized TMD widths using HERMES multiplicities in semi-inclusive deep-inelastic scattering

M. Albright[1], S. Dolan[2], A. Duong[2], L. Gamberg[2], D. Pitonyak[2], A. Prokudin[2,3], Z. Scalyer[2], D. Xu[2]

[1] College of Engineering, Penn State University
[2] Division of Science, Penn State University Berks
[3] Theory Center, Jefferson Lab, Newport News

INTRODUCTION

Protons and neutrons (nucleons), which make up the nucleus of an atom, are not fundamental constituents of matter, but rather are themselves made up of particles called quarks. These quarks are "glued" together by the strong nuclear force, which is mediated by another particle called the gluon. Any particle containing quarks and gluons is called a hadron. Moreover, the quarks are not static inside of a nucleon – they have an intrinsic momentum even for a nucleon at rest. One of the ways to access this intrinsic motion is through a process called semi-inclusive deep-inelastic scattering (SIDIS). In this reaction, a high-energy electron scatters off of a quark inside of the nucleon. This quark forms a hadron in the final-state (e.g., a pion), which is detected along with the scattered electron (see Fig. 1).

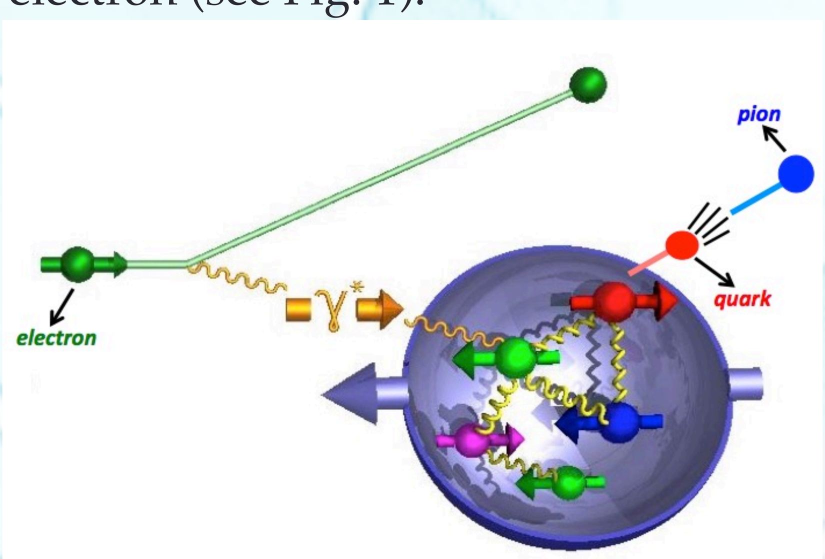


Figure 1: Schematic diagram of semi-inclusive deep-inelastic scattering (SIDIS): a high-energy electron knocks a quark out of the nucleon. The quark forms a pion in the final state, which is detected along with the scattered electron.

THE PURPOSE

The purpose of this project is to perform a phenomenological analysis of SIDIS data from HERMES on an unpolarized target. This study gives us information on the intrinsic motion of quarks inside nucleons, which is encoded in the so-called transverse momentum dependent functions (TMDs). Knowledge of TMDs allows one to create 3-D maps of the longitudinal and transverse momenta of partons (quarks and gluons) in the nucleon.

THE DATA

The data used in this analysis is from the HERMES Collaboration. The experiment scattered 27.6 GeV electrons on an unpolarized proton or deuteron target and detected either pions or kaons in the final state. Measurements were made of the hadron multiplicity, defined as the ratio of the SIDIS to the inclusive DIS cross sections for a particular target n and hadron h:

$$M_n^h(x_B,Q^2,z_h,P_{hT}) \equiv \frac{1}{\frac{d^2\sigma^{DIS}(x_B,Q^2)}{dx_B dQ^2}} \frac{d^4\sigma(x_B,Q^2,z_h,P_{hT})}{dx_B dQ^2 dz_h dP_{hT}}\,.$$

HERMES collected data for $1 < Q^2 < 10$ GeV^2, $0.023 < x_B < 0.6$, $P_{hT} < 2$ GeV, and $0.1 < z_h < 0.9$. Some of the data is shown in Fig. 2.

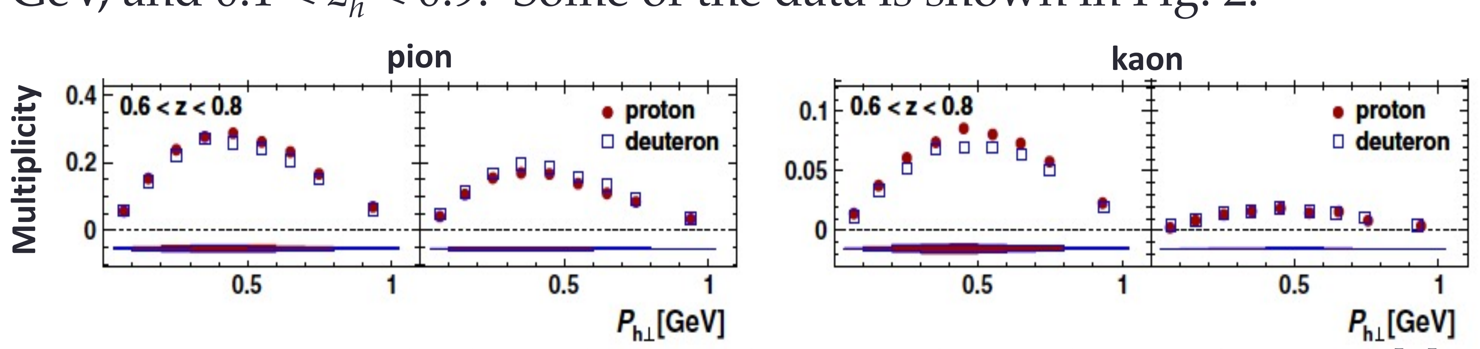


Figure 2: HERMES multiplicity data as a function of P_{hT}. Plots are from Ref. [1]

THE MODEL

The production of charged pions $\pi^+(u\bar{d}), \pi^-(\bar{u}d)$ and kaons $K^+(u\bar{s}), K^-(\bar{u}s)$ in SIDIS at low transverse momentum is described as a convolution of TMD distribution and fragmentation functions:

$$\frac{d\sigma}{dP_{hT}^2} \sim \int d^2k_\perp d^2p_\perp f(x,k_\perp^2) D(z,p_\perp^2) \delta^{(2)}(z\vec{k}_\perp + \vec{p}_\perp - \vec{P}_{hT})$$

The transverse motion of the quarks is approximated through parton model kinematics into the observed transverse momentum of the hadron. This enables us to gather information from SIDIS for exploration of TMDs. We use the following parameterizations for TMD distribution and fragmentation functions [3]:

$$f(x,k_\perp^2) = f(x)\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle} \qquad D(z,p_\perp^2) = D(z)\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$$

where $f(x), D(z)$ are the parton distribution and fragmentation functions for a particular quark type, and $\langle k_\perp^2\rangle$, $\langle p_\perp^2\rangle$ are parameters that characterize the widths of TMD distributions. In our description of HERMES data, we use 6 parameters to describe the widths:

$$\langle k_\perp^2\rangle_{valence}\,,\ \langle k_\perp^2\rangle_{sea}\,,\ \langle p_\perp^2\rangle_{\pi^+ fav}\,,\ \langle p_\perp^2\rangle_{\pi^+ unfav},\ \langle p_\perp^2\rangle_{K^+ fav}\,,\ \langle p_\perp^2\rangle_{K^+ unfav}$$

which correspond, respectively, to a universal width for valence quarks (u_v, d_v) in the proton, a universal width for all sea quarks in the proton, and four widths for the favored (e.g., $u \to \pi^+, \bar{s} \to K^+$) and unfavored (e.g., $d \to \pi^+, s \to K^+$) fragmentation into a π^+ or K^+.

Using this model, the HERMES multiplicity can be written as

$$M_n^h(x_B,Q^2,z_h,P_{hT}) = 2P_{hT}\frac{\pi\sum_a e_a^2 f_{a/n}(x_B)\,D_{h/a}(z_h)}{\sum_a e_a^2 f_{a/n}(x_B)}\,\frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle_a}}{\pi\langle P_{hT}^2\rangle_a}\,, \quad (1)$$

where $\langle P_{hT}^2\rangle_a = \langle p_\perp^2\rangle_a + z_h^2\,\langle k_\perp^2\rangle_a$ and a is the quark flavor.

DATA SELECTION AND ANALYSIS

We apply Eq. (1) to the data using appropriate isospin relations for the proton and deuteron targets. The analysis of the data will be done using the standard χ^2 minimization procedure. The main objective of our analysis is understanding of the correct criteria for data selection. A recent paper [2] studied SIDIS process and limits of TMD factorization. The authors propose a criteria for identifying the current fragmentation region — the kinematical region where a factorization picture with fragmentation functions is appropriate for studies of transverse-momentum-dependent (TMD) functions - based on a rapidity selection filter of the data. We apply a cut on the boost invariant difference of the target nucleon rapidity, and the produced hadron rapidity in the Breit frame, $y_P - y_h$. It was pointed out that for current region this difference should be of order of 3-4 units in rapidity. In our fits we introduce a set of cuts motivated by validity of TMD factorization [2]:

$$z > 0.2 \quad z < 0.6 \quad Q^2 > 1.69\ (\mathrm{GeV}^2) \quad P_{hT}/z < 0.5Q$$

RESULTS

We perform the analysis of HERMES data using new cuts and $y_p - y_h$. The number of data points range from 460 for $y_p - y_h > 1.5$ to 47 for $y_p - y_h > 3.7$ and the $\chi^2/d.o.f$ range from 1.4 to 1.3. We see that cuts in rapidity have impact on the fitted values of parameters. We show fits for $y_p - y_h > 2.5$ for 441 data points fitted using nested sampling algorithm [4]. Results are presented in Figs. 3, 4.

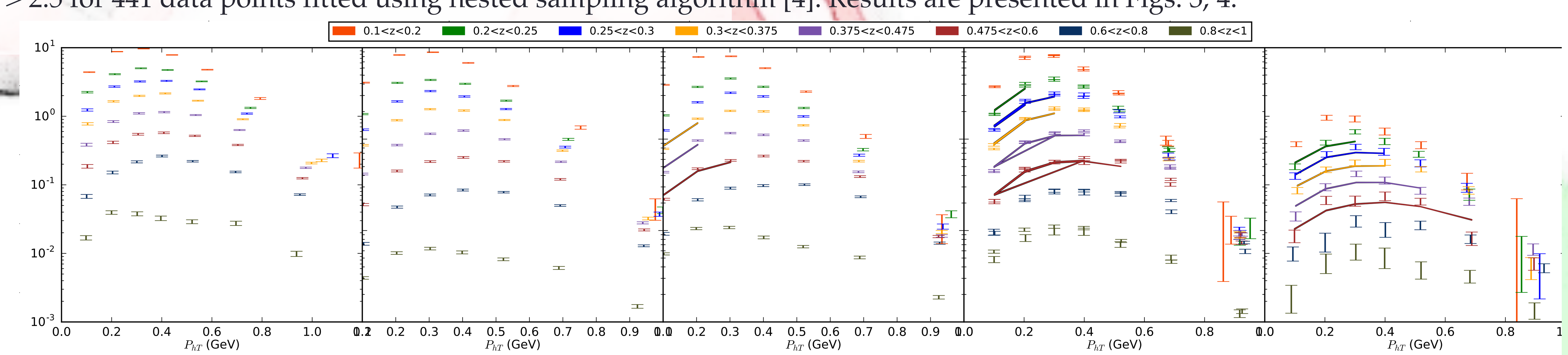
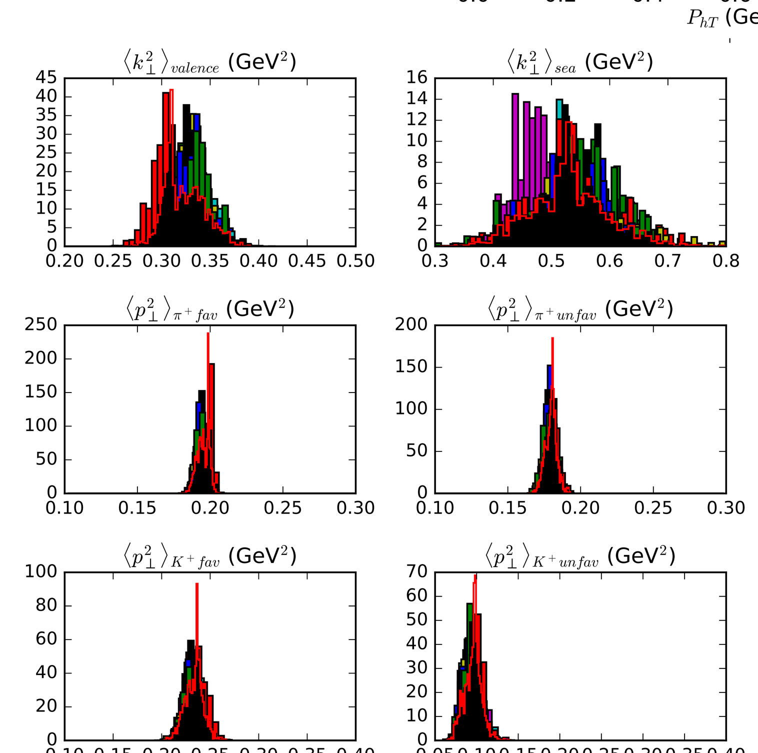


Figure 3: Description of HERMES multiplicity data as a function of P_{hT} for positive pion production.



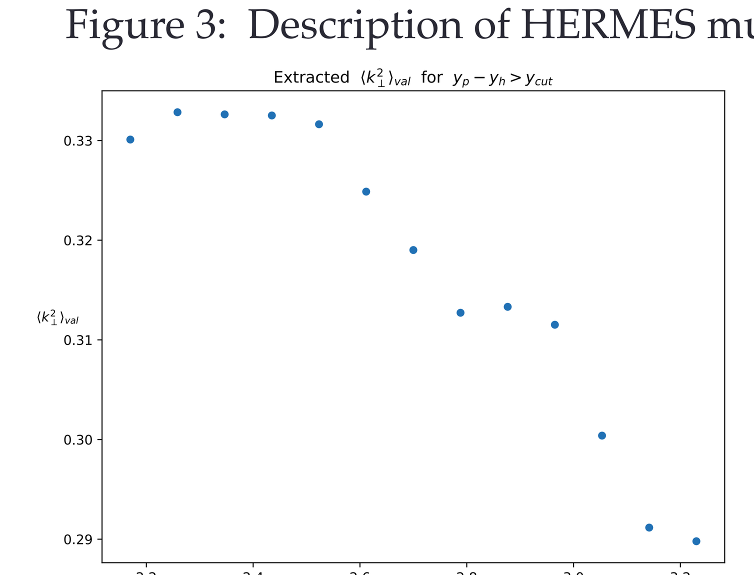


Figure 4: **Left**: Histograms of distribution of parameters after nested sampling [4] . **Right**: Extracted values of valence width as function of rapidity cut.

CONCLUSIONS AND OUTLOOK

We performed a phenomenological analysis of HERMES data on the electroproduction of charged pions and kaons from both proton and deuteron targets. The determination of the nonperturbative parameters of TMDs requires very careful selection of the experimental data compatible with factorization. We suggest that cut in rapidity can be used for such a selection.

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