Quark Propagation and Hadron Formation
Experiment PR12-06-117

W.K. Brooks, J.G. Gilfoyle, K. Hafidi, H. Hakobyan, K. Hicks, M. Holtrop, K. Joo, G. Niculescu, I. Niculescu, L. Weinstein, M. Wood, *spokespersons*.

A. Accardi, F. Arleo, S. J. Brodsky, C. Ciofi degli Atti, B.Z. Kopeliovich, E. Levin, A. Majumder, U. Mosel, A. Mueller, S. Peigne, H.-J. Pirner, Ivan Schmidt, M. Strikman, J. Qiu, X.-N. Wang, *theory proponents.*

Jefferson Lab Experiment PR12-06-117, *Quark Propagation and Hadron Formation,* was approved in 2006 by PAC 30. Since that time there have been many new developments concerning the related physics topics, which we summarize in this document. These developments only serve to increase the relevance and urgency of the original proposal; this 12 GeV experiment will provide a definitive study that can only be carried out with CLAS12 at JLab, while offering important connections to other experiments at higher energies. In the following pages, a number of observables are discussed, together with the associated physics, emphasizing the new developments of the past four years. These new developments consist of (1) additional publications and analyses of HERMES data, (2) analysis of the CLAS EG2 DIS data on nuclear targets[1], and (3) progress in theoretical understanding of existing data and of potential future measurements, including recent reviews and workshops[2]. For reference, the original proposal is located at http://www.jlab.org/exp_prog/proposals/06/PR12-06-117.pdf.

Production lengths and p_T broadening

In Deep Inelastic Scattering (DIS), seen in the target rest frame and for events with $x_{Bj}>0.1$, the virtual photon is absorbed by a single quark[3], transferring all of its energy and momentum to the struck system. The struck quark subsequently separates from the residual system (see Fig. 1) and propagates as a colored object for some time τ_p, covering a distance l_p, before becoming part of a color-singlet "pre-hadron" which evolves into a full hadron over some time τ_f and distance l_f. (l_p and l_f are the production length and the formation length, respectively.) While this classical picture underlies the conceptual framework of DIS, many details are unknown. The essence of this experiment is to study this process, embedded in nuclei of varying sizes, and use the interaction with the nuclear medium to 'measure' distance scales and understand the mechanisms involved. It can be argued that one can directly measure the production length l_p by studying p_T broadening of pions produced in nuclei, as explained in the following paragraphs. Quantitative measurements of the production length will be an important key to a microscopic understanding of the hadronization process.

A colored quark that travels through the vacuum as a quasi-free object radiates colored gluons. This process is the essential mechanism for the eventual restoration of color neutrality to all participants in the interaction, i.e., it is the mechanism for the enforcement of confinement. The vacuum radiation of a propagating quark is large, and in the pQCD picture depends on the quark virtuality Q^2. An indication of the size of the vacuum radiation loss is given from the value of the string tension in the string model, ~ 1 GeV/fm, which can be heuristically interpreted as the loss in energy due to gluon radiation per unit distance traveled in vacuum.

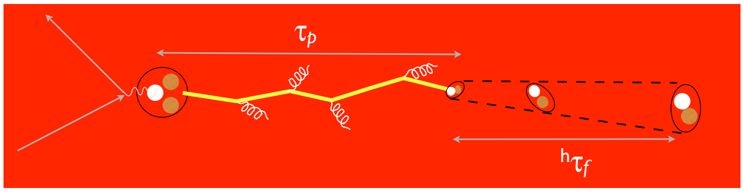


Figure 1. Cartoon of the DIS process, showing the parton propagation phase characterized by production time τ_p, *and the hadron formation phase characterized by formation time* τ_f.

In strongly interacting media, such as a cold nucleus or a hot quark-gluon plasma, the amount of energy loss due to gluon emission is expected to increase in proportion to the gluon density of the medium. In a cold nucleus, the medium-stimulated energy loss is anticipated to be much smaller than the vacuum energy loss. The new confirmation of this expectation since 2006 has been the CLAS EG2 and HERMES data for p_T broadening[4], both of which have found quite small values ranging from 0.01 to 0.05 GeV^2 for a variety of nuclear sizes (see Fig. 2). This small value means that the quark-level multiple scattering that stimulates the radiation is small.

Although the partonic multiple scattering appears to be small, the HERMES and JLab data are quite precise enough to make statements about the functional form of the p_T broadening. In Fig. 2, the data are compared to solid lines that indicate proportionality to $A^{1/3}$. While the HERMES data are reasonably consistent with a straight line, the JLab data clearly fall below the curve for the heaviest nucleus (lead). Under the assumption that this is due to the production length being less than the diameter of the lead nucleus, it allows an extraction of the production length to be performed. This statement was first made in the 12 GeV proposal, based on the foundation of earlier work[5]. Now, using the CLAS EG2 π^+ data, an extraction has been performed[6] using a simple geometric model, improving on previous efforts[7] that focused on the ν dependence. This geometric model requires further refinement, however, as a proof of principle it is adequate. Fig. 3 shows the results of fits with a 3-parameter version of the geometric model that simultaneously fits the pT broadening and the hadron absorption from the CLAS EG2 data. The production length $\boldsymbol{l_p}$ was extracted as a function of Q^2, ν, and z; in this very simple model it is consistent with 2 fm for these data. The model can be improved and a publishable result can be obtained. However, the 12 GeV measurement will be the ultimate one, since a much wider range of Q^2 and ν will be accessible, and a wider variety of hadrons can be used, with 5 target nuclei to adequately constrain the shape. With the 12 GeV data it should be possible to map the transition from the non-linear Δp^2_T vs. $A^{1/3}$ to the linear relationship, as time dialation increases the production length with increasing ν for fixed z and Q^2. It is also crucial to see the behavior with Q^2, where from basic principles of pQCD it is expected that the rate of energy loss will increase dramatically with this variable[8].

Returning to the question of medium-stimulated quark energy loss, once we have a precise measurement of the production length $\boldsymbol{l_p}$ it is possible to extract the widely-used parameter known as the transport coefficient, $\hat{q}$. The transport coefficient $\hat{q}$ expresses the amount of p_T broadening per length that is measured, and it is the most important parameter in the propagation of partons through matter. For instance, at high enough energy the medium-induced quark energy loss is proportional to this parameter in essentially any pQCD-based calculation. As noted in a recent paper[9], *partonic* broadening is related to *hadronic* broadening by a factor z^2 where $z=E_{hadron}/\nu$ is the usual kinematic variable. Thus, for a typical value of pion broadening (as measured by HERMES and CLAS) of 0.03 GeV^2 for z=0.5, the transport coefficient $\hat{q} = (0.03/0.5^2)/2\ GeV^2/fm = 0.06\ GeV^2/fm$. This result, when refined, is publishable and is of high interest. It may be compared to theoretical estimates[10] for cold nuclear matter, and can be extrapolated under certain assumptions to hot dense matter. The existing extractions for this quantity in cold nuclear matter vary greatly and precise measurements would be of high value. A much improved study will be feasible with the 12 GeV upgrade, both in terms of kinematic coverage and cross comparison of results from different hadrons.

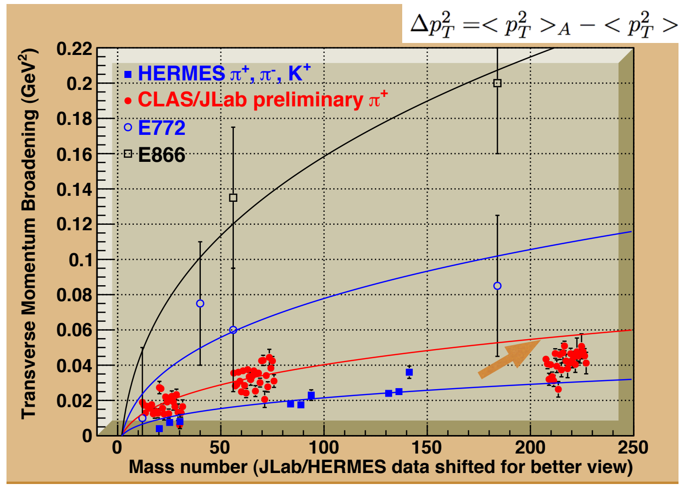


Figure 2. Data for transverse momentum broadening from Drell-Yan and DIS experiments for a variety of nuclei and hadrons.

These studies are having an increasingly important relationship to the study of hot, dense matter in relativistic heavy ion (RHI) collisions. Significant theoretical attention is now being devoted to formalisms which can treat DIS and RHI on an equal footing, inter-comparing the two to gain an increased understanding of fundamental quark-gluon interactions. Publications and activity since 2006 from the pQCD perspective include recent work by Majumder[11], by Accardi[12], by Wang[13], by Arleo and Peigne[14] and by Vitev[15]. Comparative studies of the contributions of quark energy loss and hadron attenuation in the RHI have been performed by Kopeliovich, Potashnikova, and Schmidt[16], inspired by the considerations of these processes in DIS. Similarly, the role of the production length has been highlighted in very recent work on RHI physics that aims to explain jet suppression of heavy quarks[17], with predictions that can be tested with the 12 GeV data for light quarks.

Recent work by Kopeliovich and collaborators[18] has made a very direct connection between the saturation scale of nuclei and the p_T broadening in the nuclear rest frame. Within the color dipole formalism, these authors argue that the saturation scale is identically equal to the p_T broadening. This reinforces the idea mentioned above that p_T broadening is always sensitive to the gluon density of a medium, independent of the details. The long-anticipated phenomenon of gluon saturation[19] is of high interest to several different communities, including those who are interested in the future Electron Ion Collider and LHeC, RHI collisions at RHIC and LHC, and diffractive QCD. A full development of this topic is beyond the scope of this document, but it will provide an important bridge between the 12 GeV upgrade and higher-energy facilities, particularly the Electron Ion Collider, where it could be explored over a wide range in ν.

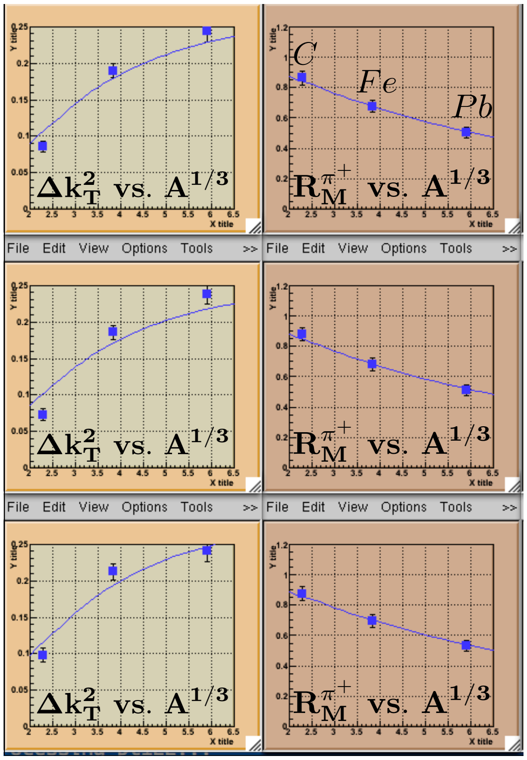


Figure 3. Simultaneous fits to the transverse momentum broadening (left column) and hadronic multiplicity ratio (right column) within a 3-parameter geometric model.

The final topic is the connection of these studies to those of the Drell-Yan (D-Y) reaction in p-A scattering, in particular, progress in this area since 2006. Fig. 2 shows data for p_T broadening from D-Y experiments with 800 GeV protons on nuclear targets. Since 2006, a new measurement, E906, has been approved at FNAL with 120 GeV. The experiment was funded by DOE Nuclear Physics in 2006, running was approved by FNAL in 2008, the spectrometer was constructed over the past two years, and a commissioning run is scheduled for July 2010; data taking is scheduled for 2010, 2011, and 2013. The data from this experiment will be very relevant to compare to the CLAS EG2 data and to the data from the 12 GeV upgrade. In addition to this approved experiment that starts in 2010, the Brookhaven National Lab program advisory committee considered two letters of intent for new D-Y measurements in the June 2010 PAC meeting[20]. Thus, several new datasets may become available in the same timeframe as the 12 GeV era.

In the case of D-Y, the partons propagating through the nucleus will experience an initial state interaction, unlike in DIS, and the distance over which they propagate within the nucleus will vary for reasons that are different from the DIS case; further, there is no hadron propagation phase. Thus, inter-comparison of these two types of data for parton propagation through cold matter will be very instructive and will provide a stringent test of the basic ideas. The theoretical community studying these problems is well-connected to the DIS and RHI analyses as well[21].

Hadron formation lengths and hadron attenuation

The phase of DIS that follows the parton propagation is the *hadron formation* phase. In this phase, the propagating quark of a given color finds an antiquark (meson formation) or a pair of quarks (baryon formation) such that the combination is color neutral. There is then a time evolution between the point of formation of the initial color-singlet system, which may not be in any specific mass eigenstate, and the final hadron. Theoretical progress has been made on understanding this fundamental process of perturbative fragmentation since 2006[22,23,24]. Theoretical work drawing from HERA phenomenology and from string fragmentation includes recent work by Pirner and collaborators[25]. A first-principles calculation by Kopeliovich et al.[26] in 2008 found that the role of quantum-mechanical interferences may be important in describing hadron attenuation. Predictions for hadron attenuation in the EG2 data and the 12 GeV data from CLAS12 were made by Gallmeister and Mosel in 2007[27]; in this work, they publish results for formation times and production times derived from HERMES and EMC data. New ideas have been developed for measuring medium-modified fragmentation functions[28].

Most of the emphasis in this experiment is on the propagation of the *struck quark* and measurement of the hadron that contains it. This generally simplifies the comparison to calculations, however, examples will be presented below that go beyond that assumption, such as study of strangeness production and of two-hadron measurements of broadening and attenuation.

The primary observable for derivation of hadron formation lengths is the hadronic multiplicity ratio R_h defined in equation 10 of the original proposal as:

$$R_h = \frac{\frac{1}{N_e^A}\ N_h^A}{\frac{1}{N_e^D}\ N_h^D}$$

where "A" denotes the heavy nucleus and "D" denotes deuterium, N_e is the number of inclusive electrons binned in Q^2 and ν, and N_h is the number of hadrons produced in bins in, e.g., Q^2, ν, z, p_T, and φ_{pq}.[29] In all cases R_h is used in DIS kinematics: $Q^2>1$ GeV^2, W>2 GeV. In the absence of any nuclear effects, $R_h=1$.

Measurements of R_h can be used to deduce hadron formation lengths. However, a model is needed, and thus the reaction mechanisms must be understood. One of the principal contributions of this experiment, which will have up to three orders of magnitude more integrated luminosity than HERMES, will be the definitive unraveling of the reaction mechanisms involved in these reactions on nuclei, which has ultimately not been possible with the HERMES data in spite of much theoretical effort. Once the reaction mechanisms are known unambiguously for a given hadron, and the properties of the preceding parton propagation phase are understood as discussed in the previous section, one can extract hadron formation lengths within a particular model, using both HERMES and CLAS6/12 data.

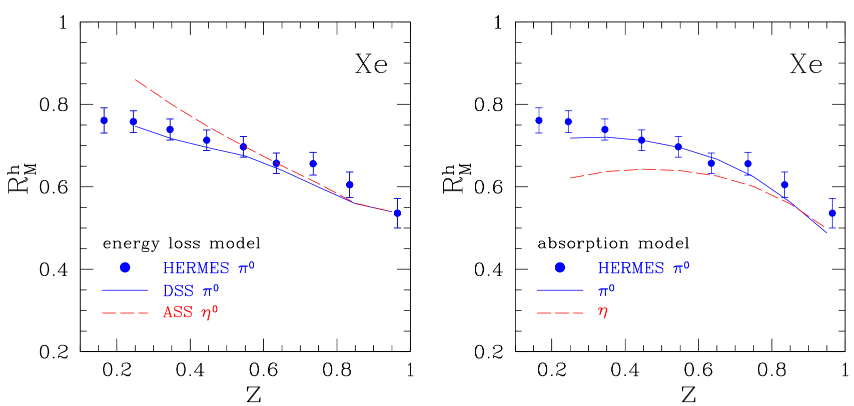


Figure 4. Multiplicity ratio for HERMES neutral pions from a Xenon target together with calculations in an energy loss model[30] calculation from 2007 and in an absorption model[31] for neutral pions and the eta meson. These calculations suggest that the comparison of η and π^0 will distinguish between these mechanisms.

An example that demonstrates where CLAS12 may be able to distinguish between two reaction mechanisms is shown in Fig. 4. This figure shows calculations from 2007 based on two different reaction mechanisms, compared to the HERMES data for neutral pions produced in a xenon target. The mechanism invoked to explain the observed attenuation in the left plot is energy loss through gluon radiation, while that in the right plot is absorption through hadronic interactions within the medium. While both approaches give a fair description of the data for π^0, the predictions for the eta meson are different and opposite in sign relative to the π^0. CLAS6 can extract first data for the η, and CLAS12 will have access to the η with significant statistical accuracy, as discussed in more detail later. This is one example out of many possibilities where the high luminosity of CLAS12 (10^{35} $cm^{-2}s^{-1}$) should be able to distinguish reaction mechanisms through model comparisons. Other examples will be noted below in the section on multi-hadron observables.

In addition to understanding the fundamental features of hadronization, a detailed understanding of hadron attenuation is also important in the study of neutrino oscillations in the GeV range. Nearly all neutrino studies are carried out with nuclear targets in order to increase the data rate. There are several fairly large effects that are due to the interactions of the neutrinos and/or the final state hadrons with the nuclei in the target. Since 2006, the MINERVA experiment (http://minerva.fnal.gov/), which has the aim of studying these effects, has been funded by the NSF (June 2006), built, and recently started taking data at full rate. Collaborative analysis efforts between CLAS and MINERVA have been ongoing using the CLAS EG2 data to date, and will continue through the 12 GeV era. A full characterization of the effects of the nuclear targets in neutrino scattering requires data from electron scattering in a comparable energy range, and there are many common aspects to the analysis of these lepton-nucleus data sets, as can be seen in the recent work of Mosel and collaborators[32], where the same code is used for both topics.

HERMES publications on p_T broadening and hadron attenuation since 2006 include: the publication on p_T broadening of π^+, π^-, *and* K^+ in helium, neon, krypton and xeon in 2010[33] and the multiplicity ratio analysis for π^+, π^-, π^0, K^+, K^-, p, and $\bar{p}$ on krypton and xenon in 2007[34]. In addition to these publications, there is a new analysis of HERMES data that is examining two-dimensional multiplicity ratios[35], i.e., studying the dependences of R_h on *pairs* of variables from the set Q^2, ν, z, p_T. With the CLAS EG2 data we have sufficient statistics to look at 3-D distributions for the highest-rate hadron (π^+), although for other hadrons the statistics are poorer. With the 12 GeV data the situation will be even better. The HERMES 2-D studies are an indication of the strong level of interest that has developed in this topic, and thus far they have found some unexpected and interesting correlations that require further investigation.

Multi-hadron observables

The study of multi-hadron processes can be expected to add additional discriminating power to the determination of the reaction mechanisms. This was the hope of the HERMES study published in 2006[36] of two-hadron multiplicity ratios. An example of the HERMES data and a higher-twist calculation[37] of the medium-modified di-hadron fragmentation function from 2008 is shown in Fig. 5, and examples of the included diagrams are shown in Fig. 6. There appear to be systematic differences between the calculation and the data, however, these data points are summed over hadron types and averaged over all other kinematic variables, and thus the comparison is of limited value. While the CLAS EG2 data also can be used for such studies, a meaningful comparison with a sophisticated pQCD calculation such as the one shown in these figures requires the kinematic reach and statistical precision of the 12 GeV measurement.

A completely new idea since the 2006 proposal is the study of multi-hadron p_T broadening. Naively, one may expect that the broadening observed in events where two hadrons are measured would be the same as what is seen when only one hadron is measured. However, a substantially enhanced broadening is seen for two-π^+ events in the CLAS EG2 data, as indicated in Fig. 7. While this result is too new to explain definitively, an explanation may lie in the multiplicity dependence of the pathlength of the partons through the nuclear medium[38]. More ‘central’ events that sample a longer pathlength may result both in more broadening and higher hadron multiplicity. Studies with Lepto indicate that the multiplicity for events with two π^+ is 50% greater than that for events with only one π^+ for these energies. Whether this is the correct explanation or not, it remains true that studies of all observables as a function of hadron multiplicity is a new tool to understand the mechanisms involved in these interactions, and may give a method to map out the path length dependence of these processes in the medium. CLAS12 is ideally suited for these studies because of its combination of high acceptance, high luminosity, and hadron detection capabilities.

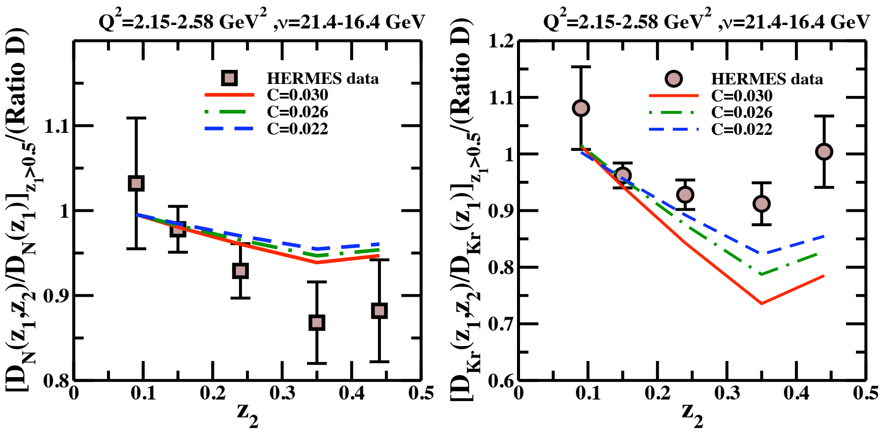
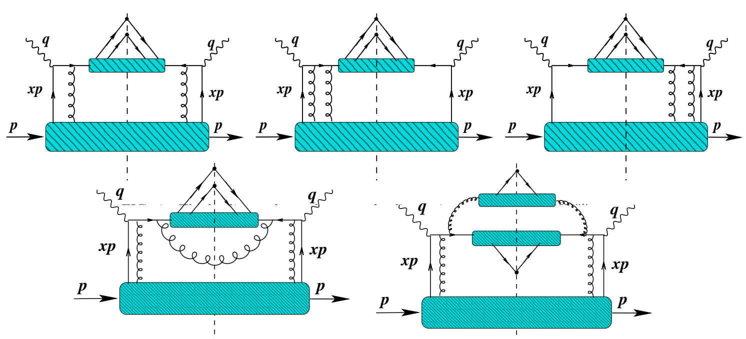


Figure 5. The HERMES data for two-hadron multiplicity ratios shown together with pQCD calculations of the medium-modified di-hadron fragmentation function at higher twist; see text.

Figure 6. Examples of diagrams included in the calculation shown in Fig. 5. The upper row shows the leading order and next-to-leading twist contribution to $W^{\mu\nu}$. The lower row shows examples of contributions at next-to-leading order and next-to-leading twist to $W^{\mu\nu}$.



Another example of multi-hadron correlations is the use of “slow protons” to understand characteristics of the target fragmentation. This has been explored in a series of papers spanning more than a decade by Ciofi and collaborators, the most recent of which was published in 2009[39]. Correlations between proton multiplicity and the forward multiplicity can also be studied[40] and these may also shed light on reaction mechanisms.

Photon-hadron correlations

A potentially important observable that will be accessible within the CLAS12 data is the correlation between the hadrons observed and photons that are measured in the CLAS12 calorimeter. One naively expects that a quark propagating through a medium, multiple scattering along the way, will radiate not only gluons, but also ordinary bremsstrahlung photons. Detailed calculations confirm this, however, they also indicate that there can be quantum interferences that enhance or suppress the process, in particular, altering the angular pattern of photon emission. Increasing attention is also being paid to photon-hadron correlations in the heavy-ion community. Both in DIS and RHI, the photons are emitted from propagating partons, and their observation will be important in understanding the gluon emission process in the medium, since the photons, unlike the gluons, emerge from the medium comparatively undisturbed.

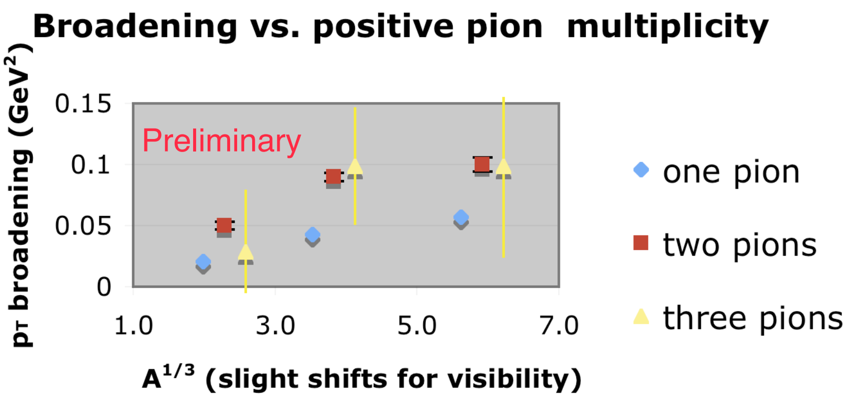


Figure 7. Transverse momentum broadening for events where 1, 2, and 3 positive pions are observed, as a function of $A^{1/3}$, from the CLAS EG2 preliminary data. See text for discussion.

The DIS case has been carefully studied in two papers published in 2008 within a pQCD approach[41]. The photon bremsstrahlung rate from a quark jet produced in DIS off a large nucleus was studied in the collinear limit. The leading medium-enhanced higher twist corrections which describe the multiple scattering of the parton in the nucleus were re-summed to all orders of twist; see Fig. 8.

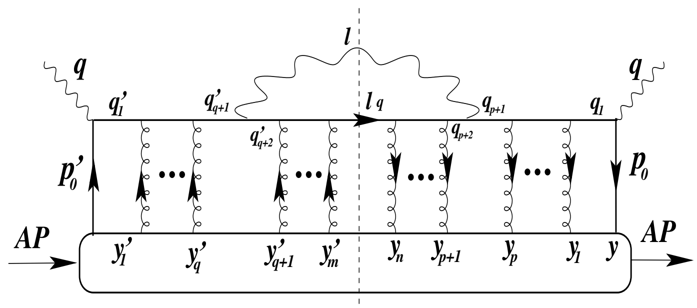


Figure 8. An order $m + n$ contribution to the single photon production rate. There are n outgoing gluons attached to the quark line on the right hand side of the cut and m incoming gluon lines on the left hand side of the cut. The photon attaches between the pth and $(p + 1)$th location on the right and between the qth and $(q + 1)$th location on the left. This contributes to twist $k \leq m + n$.

The propagation of the parton in the absence of further radiative energy loss was shown to be governed by a transverse momentum diffusion equation. In the soft-photon limit, the photon spectrum was shown to arise from two interfering sources: one where the initial hard scattering produces an off-shell quark which immediately radiates the photon and then undergoes subsequent soft re-scattering; alternatively the quark is produced on-shell and propagates through the medium until it is driven off-shell by re-scattering and radiates the photon. These processes depend in part on off-forward gluon distributions, and thus there may be sensitivity in the angular distribution of these photons to the gluon generalized parton distribution in the nucleus. This angular distribution essentially leads to a second class of transport parameter in this formalism.

Space-time information from HBT/Bose-Einstein correlations

In principle, space-time distributions can be obtained from the momentum-energy differences between identical bosons. This concept has been exploited for many decades in heavy ion collisions[42] as well as in hadron production in DIS[43]. For nuclear targets, one may use such methods to search for differences in the space-time pattern of produced pions in nuclei from the pattern on deuterium or the proton. This has been studied in the EG2 data, however, these studies were hampered by inefficiencies for close tracks in CLAS[44] as well as limited statistics for two-π^+ events. The design of CLAS12 has eliminated the close-track efficiency problem, and with its high luminosity, the sample of two-π^+ events will be much larger, allowing definitive studies to be performed.

Low-rate Hadron Production and Correlations: Drivers for the BEAM TIME REQUEST
The beam time request was discussed in the proposal in Section 7, starting on page 38. Since that time, CLAS12 acceptances have been calculated for the 10 mesons and 7 baryons listed in Table 1 of the proposal, and published in a major review article[45]. As discussed in the proposal, the beam time request is driven by the need for *completeness* in the spectrum of hadrons measured; for example, formation times are expected to depend on hadron mass, and on whether a two-quark or three-quark system is formed, among other factors. Thus, a wide spectrum of masses is needed for both baryons and mesons. Further, it is important to identify the correlations between hadrons, which requires adequate statistics. The correlations are critical for identifying reaction mechanisms, which lays the foundation for all the studies that follow. Examples of lower-rate mesons are the φ and η’, which are the only accessible mesons in their mass range. The feasibility of such studies can be evaluated using Fig. 9, which shows a strong neutral pion signal and a visible η signal for a limited range in z from the CLAS EG2 data; the η’ rate is suppressed relative to the η by an order of magnitude due to production rate and acceptance, but this will be compensated by an order of magnitude luminosity increase in CLAS12, making the η’ accessible to measurement.

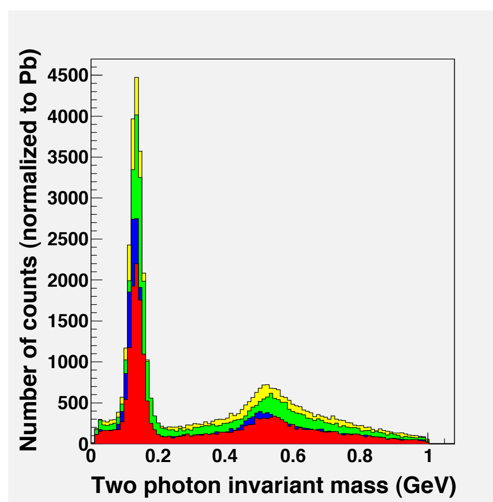
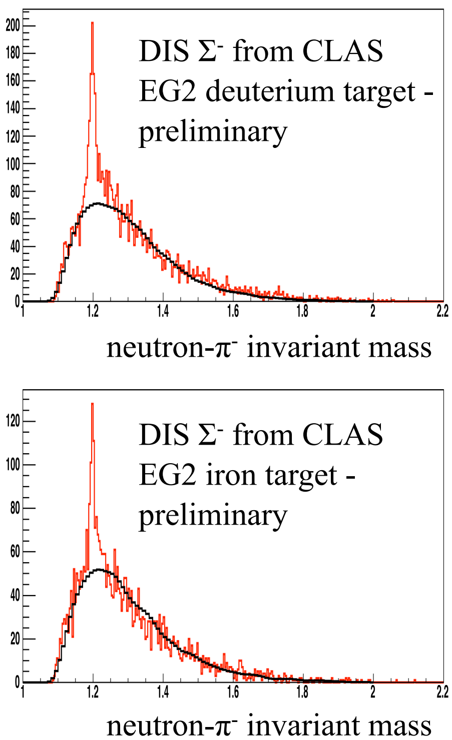
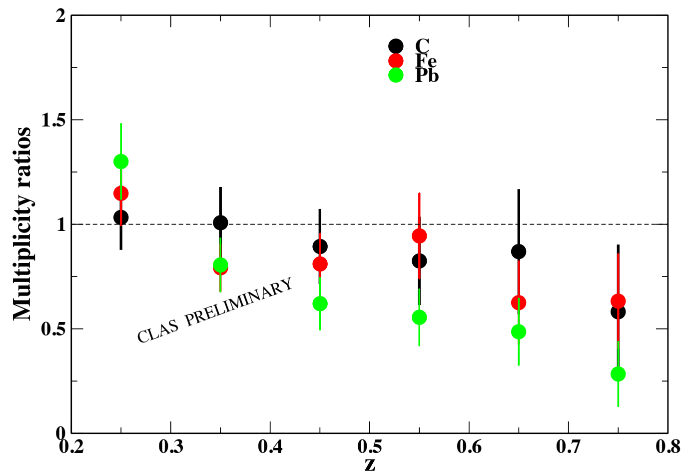


Figure 9. Invariant mass of the two-photon signals reconstructed from the CLAS EG2 data for four nuclear targets, normalized to the thickness of the lead target. The four nuclei are deuterium (in yellow), carbon (in green), iron (in blue), and lead (in red). The peaks due to neutral pions and the eta meson are visible over the combinatoric background. This plot was made by integrating over all kinematic variables within DIS kinematics except for z, which ranges from z=0.6 to z=0.7 here.

For 60 days of beam time, for $Q^2>5$ GeV^2 and z_h=0.7-0.8, and integrating over Q^2, ν, p_T and ϕ_{pq}, a 5% statistical uncertainty is expected for the φ meson[46], just enough to get a first look at the z_h dependence at intermediate Q^2. For baryons the mass range is spanned by the $\overline{p}$ and the Ξ^- and Ξ^0, all of which are produced at low rates. In 60 days of beam time, the number of collected $\overline{p}$[47], Ξ^-, Ξ^0 baryons will be 70%, 40%, and 10% of the φ meson sample in the same representative bin above, respectively, allowing first studies at low Q^2 of baryon hadronization, which is currently poorly understood even at the level of phenomenology. Examples of correlated signals requiring the requested beam time include the photon-hadron correlations discussed above, the Bose-Einstein correlation analysis, and the studies of multi-hadron correlations as a function of hadron multiplicity, for which the rate is dropping rapidly as the measured multiplicity increases.

Figure 10. Data from the CLAS EG2 experiment for lower-rate channels. (left) Plot of Σ^- mass from CLAS EG2 analysis[48] for deuterium (upper panel) and iron (lower panel). This is an important channel that will be used for the baryon hadronization studies with the 12 GeV data. (right) Preliminary data for the K^0 multiplicity ratio for carbon, iron, and lead relative to deuterium[49]. The data are integrated over Q^2, ν, p_T, and φ_{pq}.





Examples of lower-rate channels from the CLAS EG2 data are shown in Fig. 10. On the left are plots of the neutron-π^- invariant mass in deuterium (upper panel) and iron (lower panel), showing a peak from the Σ^- baryon. With data of this kind, one can begin to approach the important and poorly-understood topic of baryon hadronization. On the right is a plot of the hadronic multiplicity ratios for the K^0 meson for carbon, iron, and lead. Strangeness production can give a unique insight into the hadronization process, since the strange quark is likely to come directly from the "string-breaking" process. These are the world's only multiplicity ratios for the K^0, thus extending the existing HERMES data for K^+ and K^-. Channels such as these are strongly limited in statistical precision. In addition, the precision with which the dominant systematic uncertainties can be evaluated is also limited by the statistical quality of the data. Thus, it will be very important to obtain the ***full*** 12 GeV dataset so as to make a reliable extraction in the low-rate channels. This is crucially important for a systematic understanding of the mass and flavor dependence of meson and baryon formation.

In conclusion, the measurements proposed offer an opportunity to obtain completely new information on hadronization and the mechanisms of QCD confinement in forming systems. The level of scientific interest and activity has continued to grow since the original proposal of 2006. A comprehensive program of this nature can be carried out with the CLAS12 spectrometer and 11 GeV electron beam in 60 PAC days.

[1] The CLAS EG2 run period was a measurement with 5 GeV electron beam.The proposal for hadronization experiment E02-104 from that run period may be found at http://www.jlab.org/exp_prog/proposals/02/PR02-104.pdf. While limited in kinematic range, it can be considered as a prototype for the 12 GeV measurements. The data analyses that are currently underway with these data include the following mesons and baryons: π^+ (H. Hakobyan, W. Brooks), π^0 and η (T. Mineeva, K. Joo), proton and π^-,(R. Dupré, K. Hafidi), K^0 and $\pi^+\pi^-$ (A. Daniel, K. Hicks), f1 and ω (M. Wood), Λ (L. El Fassi, K. Hafidi), Σ^- (I. Niculescu, G. Niculescu). Several of these studies are nearing the publication stage.

[2] http://arxiv.org/abs/0907.3534; http://arxiv.org/abs/1002.2206, http://arxiv.org/abs/0810.5702, http://arxiv.org/abs/0804.2021

[3] V. Del Duca, S. J. Brodsky and P. Hoyer, Phys. Rev. D46, 931 (1992). See also: A Bound on the energy loss of partons in nuclei, S. J. Brodsky, P. Hoyer, Phys. Lett. B298:165-170,1993, hep-ph/9210262.

[4] The definition of p_T broadening is $\Delta p^2_T=(\langle p^2_T\rangle)_A-(\langle p^2_T\rangle)_D$ where A is the larger nucleus and D is deuterium, and the average value of the p^2_T spectrum is $\langle p^2_T\rangle$; the transverse direction is defined with respect to the axis defined by the virtual photon direction.

[5] http://arxiv.org/abs/hep-ph/0311220

[6] W. Brooks, private communication, and http://indico.cern.ch/getFile.py/access?contribId=334&sessionId=10&resId=1&materialId=slides&confId=86184 (Talk at DIS 2010)

[7] http://arxiv.org/abs/hep-ph/0608044

[8] http://arxiv.org/abs/1004.3920

[9] Transverse Momentum Broadening in Semi-inclusive DIS on Nuclei, S. Domdey, D. Grunewald, B.Z. Kopeliovich, H.J. Pirner, Nucl. Phys. A825:200-211,2009, arXiv:0812.2838 [hep-ph]. See also: Higher Twist Effects in Deep Inelastic Scattering on Nuclei, H.J. Pirner, D. Grunewald, Nucl. Phys. A782:158-165,2007, hep-ph/0608033.

[10] http://arxiv.org/abs/hep-ph/9608322

[11] http://arxiv.org/abs/0912.2987, http://arxiv.org/abs/0901.4516, http://arxiv.org/abs/0810.4967

[12] http://arxiv.org/abs/0706.3227, http://arxiv.org/abs/nucl-th/0609010

[13] http://arxiv.org/abs/1001.3146, http://arxiv.org/abs/0910.3403, http://arxiv.org/abs/0704.0106

[14] http://arxiv.org/abs/1006.0818

[15] http://arxiv.org/abs/0806.0003, http://arxiv.org/abs/hep-ph/0703002

[16] http://arxiv.org/abs/0707.4302

[17] http://arxiv.org/abs/1004.3920

[18] http://arxiv.org/abs/1001.4281

[19] L. V. Gribov, E. M. Levin, and M. G. Ryskin, Phys. Rept. 100 (1983), 1.; A. H. Mueller and Jian-wei Qiu, Nucl. Phys B268 (1986), 427; L. L. Frankfurt and M. I. Strikman, Phys. Rept. 160 (1988), 235; http://arxiv.org/abs/hep-ph/0011241.

[20] http://www.bnl.gov/npp/pac0610.asp

[21] http://arxiv.org/abs/hep-ph/0701015; http://arxiv.org/abs/hep-ph/0605200; http://arxiv.org/abs/hep-ph/0606126

[22] http://arxiv.org/abs/0801.0251

[23] http://arxiv.org/abs/0706.3059

[24] http://arxiv.org/abs/0904.1450

[25] http://arxiv.org/abs/0812.2838

[26] http://arxiv.org/abs/0809.4613

[27] http://arxiv.org/abs/nucl-th/0701064

[28] http://arxiv.org/abs/0810.1193

[29] The semi-inclusive hadron production process (e,e'h) depends on five kinematic variables. Here we generally use the four-momentum transfer Q^2, the energy transfer ν, the fractional hadron energy $z=E_{hadron}/\nu$ (as also defined on page 3), the hadron momentum component transverse to the virtual photon direction p_T, and the azimuthal angle around the virtual photon direction ϕ_{pq}. Other choices of variables are possible; we integrate over some variables to maintain statistical accuracy.

[30] A. Accardi, Phys. Rev. C76:034902,2007, http://arxiv.org/abs/0706.3227. Fragmentation functions used are: (pions) DSS = de Florian D, Sassot R and Stratmann M 2007 Phys. Rev. D 75 114010 and de Florian D, Sassot R and Stratmann M 2007 Global analysis of fragmentation functions for protons and charged hadrons, Preprint arXiv:0707:1506 [hep-ph]; (eta) ASS = Aidala, Sassot, Strattmann, unpublished

[31] A. Accardi, D. Grunewald, V. Muccifora, and H.J. Pirner, Nucl. Phys. A761:67-91, 2005, http://arxiv.org/abs/hep-ph/0502072

[32] http://inspirebeta.net/search?ln=de&p=f+a+leitner+and+a+mosel&f=&action_search=Suchen

[33] http://arxiv.org/abs/0906.2478

[34] http://arxiv.org/abs/0704.3270

[35] http://indico.cern.ch/contributionDisplay.py?contribId=146&confId=86184, contribution to DIS2010 entitled "Nuclear attenuation - 2 D dependencies at HERMES (presented by K. Rith)" on 20 April 2010.

[36] http://arxiv.org/abs/hep-ex/0510030

[37] http://arxiv.org/abs/0806.2653

[38] B. Z. Kopeliovich, private communication.

[39] http://arxiv.org/abs/0911.1377; http://arxiv.org/abs/0705.3617; http://arxiv.org/abs/nucl-th/0505042; http://arxiv.org/abs/hep-ph/9904486.

[40] L. Frankfurt and M. Strikman, Physics Reports 160 (1988) 235.

[41] http://arxiv.org/abs/0705.1147v4, http://arxiv.org/abs/0711.2475

[42] http://arxiv.org/abs/nucl-ex/0505014

[43] http://arxiv.org/abs/0706.2538v1, Phys. Lett. B652:1-12, 2007.

[44] Mestayer et al., NIM A 524 (2004) 306–313.

[45] http://arxiv.org/abs/0907.3534; CLAS12 acceptance calculations are shown in Fig. 67 for the mesons and baryons listed in Table XII.

[46] This estimate is based on a parametric acceptance calculation for CLAS12, and on the LEPTO event generator. It does not take into account the additional losses from, e.g., non-functioning detector elements and background subtractions for the φ meson. The uncertainties due to the background subtractions will be much smaller if the proposed RICH detector for CLAS12, which is needed for several approved experiments, is available. The RICH detector will significantly reduce the combinatoric background of positive hadrons under the narrow φ meson peak in the sectors in which it is available, improving the uncertainties in the measurement. For the η' meson, the acceptance at a given energy will be the same as for CLAS6, since it will be reconstructed in the CLAS forward calorimeters. In this case, the rate is higher than for the φ meson, however, the peak will be broader, and thus the background subtraction procedure will be an additional factor in determining the statistical and systematic uncertainties of the measurement.

[47] The inclusion of three hadrons in this program will require the proposed RICH detector for CLAS12, which is needed for several other approved experiments. These hadrons are the charged kaons K^+ and K^-, and antiprotons at highest momentum. All other hadrons will be experimentally accessible, however, the RICH detector will also reduce the uncertainties for φ, as well as reduce uncertainties for any decay resulting in a highest-energy hadron.

[48] I. Niculescu, G. Niculescu, private communication.

[49] A. Daniel, K. Hicks, Proceedings from the XVIII International Workshop on Deep-Inelastic Scattering and Related Subjects (2010), in preparation. See also "K_s^0 Hadronization Following DIS at CLAS," K. Hicks and A. Daniel, Proceedings of the XVII International Workshop on Deep-Inelastic Scattering and Related Topics, Madrid, Spain, April 2009, http://www.ft.uam.es/DIS2009/ and http://arxiv.org/abs/0907.5362.