Run Group E Jeopardy Update

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(Dated: June 2020)

Run Group E consists of Jefferson Lab experiment E12-06-117 "Quark Propagation and Hadron Formation" which was originally approved in 2006 and later given the scientific rating of "A^-" by PAC 36 in 2010[15]. The experiment will make use of nuclear targets to gain substantial new insights into the propagation of QCD color through strongly interacting systems. There are two essential thrusts of these studies. First, we seek to characterize the fundamental QCD subprocesses of color propagation and hadron formation in quark fragmentation, extrapolating from observations with nuclear targets to the more general cases of proton targets or the early universe[2]. Second, we seek to greatly expand our knowledge about the color structure of nuclei from these studies by using the struck quark as a colored probe of the medium. By studying the strength of the interaction between the colored quark and the nuclear medium using the transport coefficient $\hat{q}$, we gain quantitative understanding of the color structure of bound nucleons via color charge form factors[7]. An extraction of the $\hat{q}$ transport coefficient was recently performed by members of our collaboration[4]. The same analysis will be carried out on the data from our 12 GeV experiment, and will measure the multivariate dependence of $\hat{q}$, promising an enormous advance in our understanding of the color structure of nuclei.

I. PHYSICS GOALS AND NEW DEVELOPMENTS

The first physics aim of the experiment is to explore fundamental characteristics of color propagation and hadron formation. These processes are unique to QCD because of the non-Abelian nature of the strong interaction that confines quarks into hadrons. With the data from this experiment we will extract the color lifetime of quasi-free quarks during the brief time that they are liberated following a hard interaction in DIS kinematics. This time is at the femtometer scale, and thus it can only be directly measured by the interaction within nuclei, which have dimensions of that same scale. We will also extract the interaction cross sections of a variety of mesons and baryons and study the kinematic dependencies needed to describe their formation mechanisms.

A. Advances in Theory and Phenomenology

Recently, members of our team completed an extraction of the color lifetime for light quarks from HERMES published data[4]. The method employed by Brooks and López (BL) was to fit two observables simultaneously in a geometrical framework with realistic nuclear density distributions. The framework is not a dynamical model, but rather it makes a geometrical association between stages of the hadronization process and experimental observables, with the outcome strongly constrained by the fixed nuclear density distributions of the three heavier nuclei. The first observable, transverse momentum broadening of charged pions Δp_T^2, was associated in the framework with partonic multiple scattering over a period of time corresponding to the color lifetime. The second observable, the hadronic multiplicity ratio R_M^π, was associated with interaction of formed hadrons within the nuclear medium. An excellent fit of the data was obtained for all three of the heavier nuclei neon, krypton, and xenon in this simple physical picture with two fit parameters: the color lifetime, and the strength of the transverse quark-medium interaction. The published pion-nucleon cross sections were used for the baseline version of the model. The fit to the data is shown in Fig.1.

In the BL study the color lifetime was shown to depend on the standard SIDIS z_h observable, $z_h = E_h/\nu$, with exactly the magnitudes and functional dependence predicted by the Lund String Model (LSM). A plot of these results is shown in Fig.2, and in this figure it can be seen that the values found for the color lifetime range from

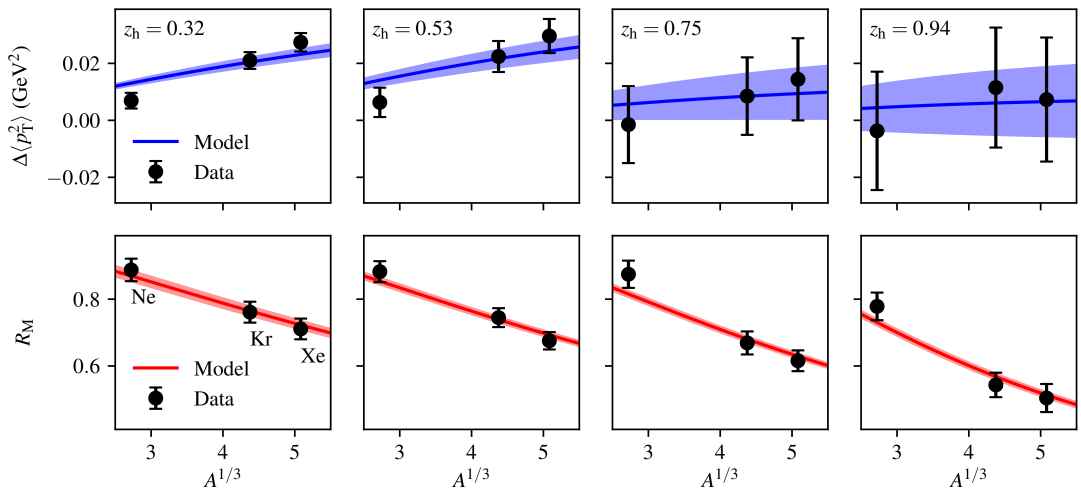

FIG. 1. Fits of the two-parameter BL model to HERMES published data. The fit is performed for two observables simultaneously in a given bin in z_h.

2 fm/c at high z_h to 8 fm/c at lower z_h. The curves in the fit correspond to two LSM analytical expression for the color lifetime. The curve labeled LSM corresponds to the color lifetime for the struck quark, and the other curve takes into account the full string evolution. If the LSM string tension is left as a fit parameter, when fitted to the color lifetimes from the BL study of the HERMES data, we find string tension values that are compatible with 1 GeV/fm, the well-known magnitude of this quantity. This result is a strong validation of the geometrical framework that was used for this analysis.

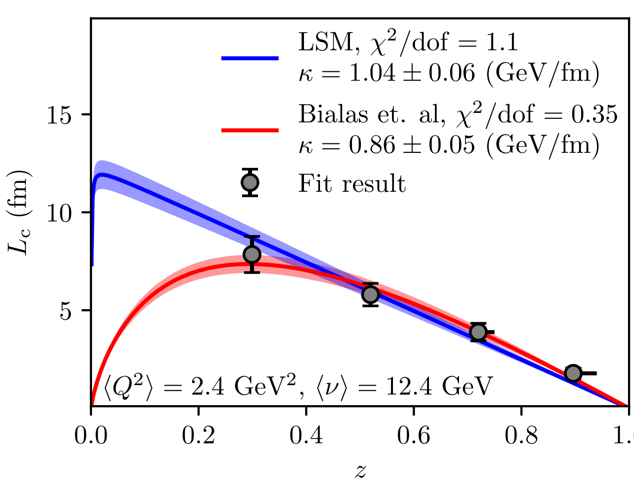

FIG. 2. A secondary fit of the results from the HERMES fit to LSM analytical expressions for the color lifetime. The curve labelled "LSM" is for the struck quark, while the other curve is from Bialas and Gyulassy[3].

There have been substantial theory advances that are directly relevant to this experiment since PAC 36 in 2010. We only list a few here, due to space constraints. In the year 2000, Guo and Qiu determined that transverse momentum broading is related to the quark-gluon correlator $T_{qg}(x_B, 0, 0)$ between energetic quarks and soft gluons[9]. Using leading order pQCD, they determined the relationship between p_T broadening and $T_{qg}(x_B, 0, 0)$ to be:

$$\Delta\langle k_{hT}^2\rangle = \left(\frac{4\pi^2\alpha_s z_h^2}{N_c}\right)\frac{\sum_q e_q^2 T_{qg}(x_B,0,0)D_{h/q}(z_h)}{\sum_q e_q^2 f_{q/A}(x_B)D_{h/q}(z_h)} \quad (1)$$

where k_{hT} is the transverse momentum of the parton that fragments into the observed hadron h, and f and D are the usual parton distribution functions and fragmentation functions. In 2016, Kang, Wang, Wang and Zing (KWWZ) reproduced this result from the year 2000 and extended it to next-to-leading-order (NLO) using the higher-twist collinear factorization framework[11]. They evaluated at NLO the transverse-momentum-weighted differential cross section $d\langle k_{hT}^2\sigma^D\rangle/dx_B dy dz_h$ at twist 4, considering contributions from quark-gluon and gluon-gluon double scatterings, as well as interferences between single and triple scatterings. They found that $d\langle k_{hT}^2\sigma^D\rangle/dx_B dy dz_h$ can be factorized as a convolution of twist-4 nuclear parton correlation functions, the usual twist-2 fragmentation function, and hard parts which are finite and free of divergences.

Last year, Ru, Kang, Wang, Xing and Zhang (RKWXZ) [19] used the insights from the above efforts to perform a global fit to a variety of types of data, including the HERMES p_T broadening, to constrain the $\hat{q}$ transport coefficient discussed earlier. The analysis took into account the world data on transverse momentum broadening in semi-inclusive electron-nucleus deep inelastic scattering, Drell-Yan dilepton and heavy quarkonium production in proton-nucleus collisions, as well as the nuclear modification of the structure functions in deep inelastic scattering, comprising a total of 215 data points

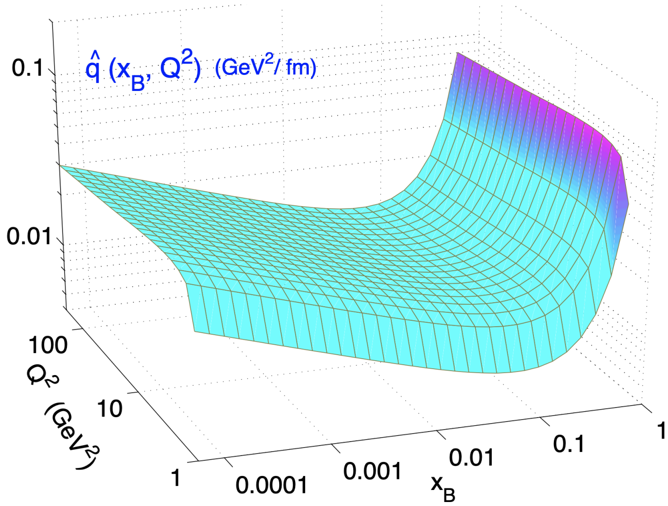

FIG. 3. Dependence of $\hat{q}$ on x_{Bj} and Q^2 found by the RKWXZ theory collaboration

from 8 data sets. Among other things, they found an interesting dependence of $\hat{q}$ on x_{Bj} and little dependence on Q^2, neither of which had never before been demonstrated with experimental data. This dependence is illustrated in Fig. 3.

With the increased statistical sample at 12 GeV, our experiment will provide the world's leading dataset for such studies at higher x_{Bj}. An example plot from the CLAS 5 GeV data is shown in Fig. 4 with three-fold dimensional bins in Q^2, z_h, and x_{Bj} for carbon, iron, and lead nuclei with respect to deuterium. At 12 GeV we will have much wider kinematic coverage and more integrated luminosity.

In other developments from the higher twist approach, in 2014 Chang, Deng and Wang studied three models for the initial state of a parton passing through a medium and compared predictions to HERMES data[5]. The initial state modeling, for example assuming the in-medium fragmentation functions are the same as for electron-proton scattering in vacuum, cannot be computed from pQCD. In order to describe the observables at the scale Q of the data, modified DGLAP equations must be used to evolve the initial state at a starting scale Q_0 using an initial state model. They determined that the magnitude of the $\hat{q}$ they extracted depended strongly on the initial state model, finding the best model fit yielded $\hat{q}$=0.02 GeV^2/fm while the most naïve model yielded values more than an order of magnitude larger.

Very recently, Guiot and Kopeliovich made an important step forward by making a description of the HERMES two-dimensional multiplicity ratio data[8]. The approach is updated from the one-dimensional formulation of Kopeliovich, Nemchik, Potashnikova and Schmidt which successfully described both HERMES data and heavy-ion collision data[12]. This new paper adds the description of the kaon multiplicity ratio of HERMES and simultaneously fits the ν and z_h dependence for π^+, K^+, and K^-. According to this work, quark energy loss plays a more minor role in describing the HERMES multiplicity ratios. The paper goes on to explore the implications for the LHC and the EIC.

In a foundational theoretical effort, in 2013 Qin and Majumder derived a differential equation for the time evolution of the momentum distribution of a hard parton traveling through the nuclear medium[18]. This equation describes in-medium evolution of hard jets which experience longitudinal drag and diffusion in addition to the transverse broadening caused by multiple scatterings from the medium. While the relative importance of longitudinal drag vs. longitudinal diffusion may not yet be clear, collisional energy loss cannot simply be neglected in a theoretically correct description. This is not only true for the suppression of single inclusive hadrons, but also for jet shower evolution, energy loss distribution within and outside the jet cone, as well as energy and momentum deposition into the medium by the jet shower. The formalism developed in this paper is applicable to jet modification in both hot and cold matter.

A comprehensive review of the theory and phenomenology of pQCD-based jet quenching was published by Majumder and van Leeuwen in 2011[14]. The review article develops the basic context of the topic, proceeds through single and multiple gluon radiation processes, mentions heavy flavors, covers modeling of the medium, and then compares the experimental data of that time to observables calculated in a variety of model approaches.

A series of seven theoretical analyses of the HERMES data and Drell-Yan data were made starting in 2010 by Song and collaborators[20][21][23][22][13][24][25]. These papers explore some of the same kinds of themes that are included in the goals of this proposal: $\hat{q}$ estimates, quark energy loss, hadron formation.

Beyond the above studies that directly address the kinds of observables we will measure, there are new theory efforts that connect more broadly to the topic of the color structure of nuclei. The $\hat{q}$ transport coefficient for high-x quarks is by definition a probe of the interaction between a colored quark and the nuclear medium that leads to exchange of transverse momentum. This conceptually connects to recent work by Dumitru, Miller and Venugopalan [7] who developed a novel light-front QCD formalism to compute color charge correlators and their associated color charge form factors. While their work specifically addresses the free proton, color charge form factors of a bound proton and neutron are clearly related to $\hat{q}$ and it can be hoped that future work will connect these ideas quantitatively.

B. Advances based on CLAS 5 GeV Data

The HERMES data, as the world's first data of its kind, had sufficient statistical accuracy to perform the study of transverse momentum broadening in only one dimension in ν, Q^2, x_{Bj}, or z_h at a time. This was due

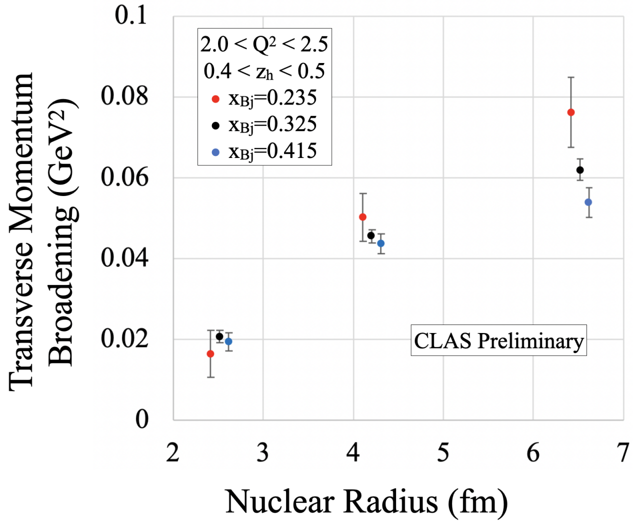

FIG. 4. Preliminary transverse momentum broadening of positive pions in the CLAS 5 GeV data for a threefold dimensional bin in Q^2, z_h, and x_{Bj} for carbon, iron, and lead nuclei with respect to deuterium. The error bars shown are statistical only. There is a hint of a dependence on x_{Bj} that is consistent with Fig. 3 but more data are needed to definitively establish the trend.

to the size of the uncertainties in Δp_T^2, which were constrained by the experimental luminosity. In our 12 GeV experiment, we will have enough statistical accuracy in this observable to study it as a function of multiple variables, and to extract the behavior of the color lifetime in those variables, using the same BL geometrical framework. Of particular importance is the dependence on ν and Q^2, because with those variables one can perform the first tests to confirm the expected time dilation of the color lifetime. The reason this is expected is that the fundamental nature of the color lifetime is that it is a time interval for a process that unfolds over a distance; while people sometimes refer to it as a "length," it will experience time dilation, not length contraction, so it is fundamentally a time interval and thus is expected to exhibit time dilation. With the kinematic breadth of the experimental coverage at 12 GeV, a definitive evaluation of time dilation will be possible, and if confirmed it would clearly establish the validity of the physical picture underlying our understanding of the hadronization mechanisms in semi-inclusive deep inelastic scattering for light quark hadrons.

The same approach can be taken with hadrons for which the observed hadron should not generally contain the struck quark, such as charged kaons and antiprotons. Because the data analyses will isolate $x_{Bj} > 0.1$, sea quarks will not be sampled, and thus the strange quarks and antiquarks in the kaons and antiprotons will emerge in higher-rank hadrons, in the LSM terminology, that originate in the middle region of the string formed, not in the end of the string as for the struck quark. These data, analyzed in a way similar to that of the BL framework, will allow the first evaluation of the rank dependence and quark mass dependence of the color lifetime, and comparison to the naïve expectations from the LSM.

The above examples address the first phase of hadronization, which consists of the propagation of colored quarks. New information about the second phase of hadronization, which is the formation of hadrons, will be accessible in the 12 GeV data as well. In the BL study, the hadronic multiplicity ratio R_M^h is associated with the interaction of the formed hadron in the nuclear medium. In that study, the baseline model made use of published data on pion-nucleon cross sections to calculate the multiplicity ratios. In a variant of this model, the pion-nucleon cross section was treated as a third fit parameter, and the values extracted this way were consistent with the published $\pi - N$ data but had large uncertainties due to the statistical limitations of the data. With the 12 GeV data we will use the same method but with much smaller statistical uncertainties. The naïve expectation is that the in-medium $\pi - N$ cross section will be smaller than the published $\pi - N$ data because the hadron is in the process of forming and thus will not have its full color field. We will test this naïve expectation by extracting the dependencies of this cross section on multiple variables, taking advantage of the high luminosity at 12 GeV.

Two-dimensional multiplicity ratios from HERMES [1] clearly demonstrated that important multi-dimensional features exist for the hadronization process in nuclei. In the CLAS 5 GeV data we have extended such studies to three-dimensional and even exploratory four-dimensional multiplicity ratios for the high-rate hadrons. An example is shown in Fig. 5 where a three-dimensional multiplicity ratio for neutral pions is shown as a function of p_T^2, z_h, and ν. The expected Cronin-type enhancement extends well above a multiplicity ratio of unity, seen here for the first time for the neutral pion, with a strong dependence on z_h, confirming the trend clearly shown by HERMES for charged mesons that high-z_h mesons are *not* enhanced at high p_T. There is also a ν dependence to the z_h dependence in that the z_h-ordering for high p_T agrees well with the ordering seen by HERMES for the two higher ν bins, while for the lowest ν bin that ordering is modified, as is the average magnitude of the enhancement at high p_T. Thus, a clear three-dimensional behavior is identified, allowing deeper probing of the mechanisms of hadronization in nuclei.

If it turns out to be feasible to extract effective in-medium meson-nucleon cross sections as in the BL analysis, this approach will allow experimental estimates of effective hadron-nucleon cross sections that are not possible to measure with a particle beam, such as total cross sections for $\phi - N$, $\omega - N$, $\eta - N$, etc. Beyond that simple model, it is clear that more sophisticated theoretical models should be applied to address in-medium interaction of forming hadrons. Such models exist and have been compared to HERMES 1D multiplicity ratios and in two cases to 2D multiplicity ratios[8][24]. We have already

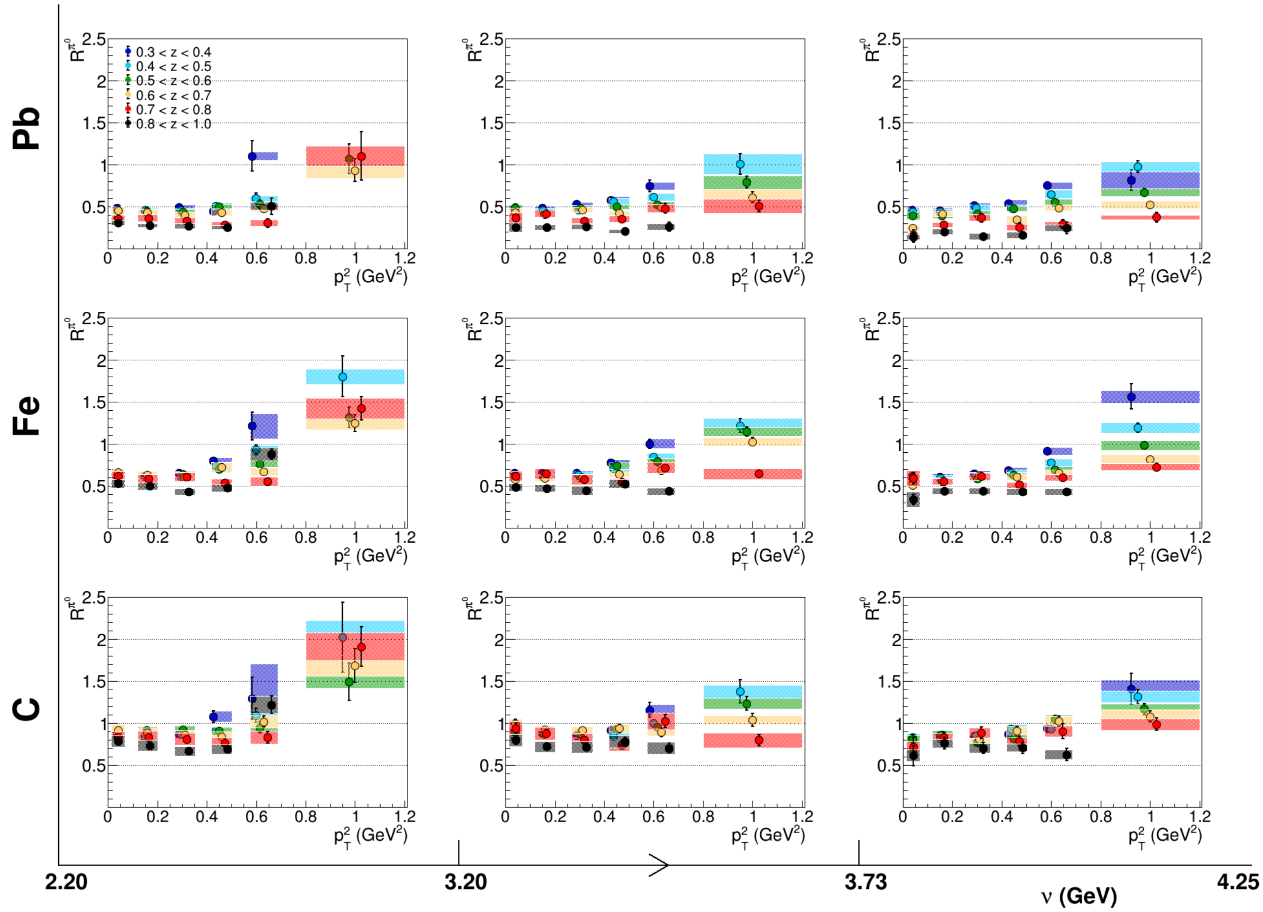

FIG. 5. Three-dimensional multiplicity ratio for neutral pions as a function of p_T^2, z_h, and ν from the CLAS 5 GeV data from the EG2 run period. Statistical uncertainties are shown by error bars, and systematic uncertainties are shown by colored bands. The points are shown staggered within the bin for better visibility.

demonstrated the capability of measuring multiplicity ratios for three heavier mesons with the 5 GeV CLAS data. These mesons, the K_S^0 (M=498 MeV, S=1), η (M=548 MeV, S=0) and ω (M=782 MeV, S=0), have relatively low production rates and are experimentally more challenging to isolate, but they are very interesting for understanding the mass and strangeness effects in hadron formation. In Figures 6 and 7 are shown preliminary multiplicity ratios for eta mesons from the CLAS 5 GeV data for the iron nucleus for z_h and p_T^2 in two decay channels. The uncertainties in these plots are only the statistical uncertainties. The data in Fig 6 show hadron attenuation to below $R_M^\eta = 0.6$, currently a greater suppression than is seen in the same dataset for the neutral pion and for the K_S^0[6]. In Fig. 7 the Cronin-type enhancement at high p_T^2 is clearly visible. In the 12 GeV experiment we will be able to probe these mesons with much better statistical precision, and will be able to add the ϕ meson (M=1019 MeV) by making use of the CLAS12 RICH particle identification capabilities. We will also be able to study the η' meson (M=958 MeV) and the f1 meson (M=1285 MeV). All of these mesons have $c\tau$ longer than the dimensions of nuclei, so they are stable probes in the relevant timeframe for these studies.

C. Promising Developments in Understanding Hadronization Mechanisms

In this section we discuss (1) source size studies using Bose-Einstein Correlations, (2) diquark degrees of freedom in baryons from baryon hadronization in nuclei, and (3) diquark degrees of freedom in baryons from dihadron studies in nuclei. In these topics we find tantalizing hints from the CLAS 5 GeV measurements that a very substantial and interesting program of studies will be possible with the 12 GeV data of CLAS on nuclear targets.

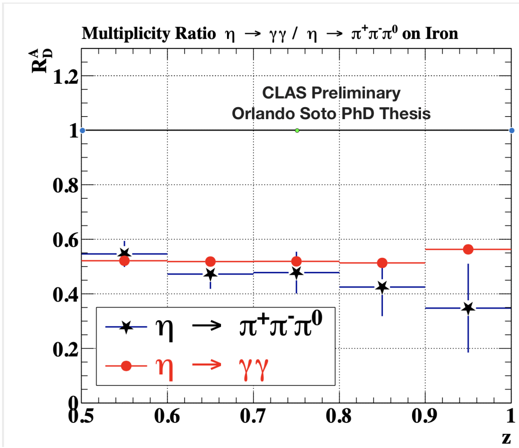

FIG. 6. Multiplicity ratios for eta mesons in two decay channels as a function of z_h from the CLAS 5 GeV data from the EG2 run period. Error bars reflect statistical uncertainties only. For the $\gamma\gamma$ decay channel the error bars are smaller than the points shown.

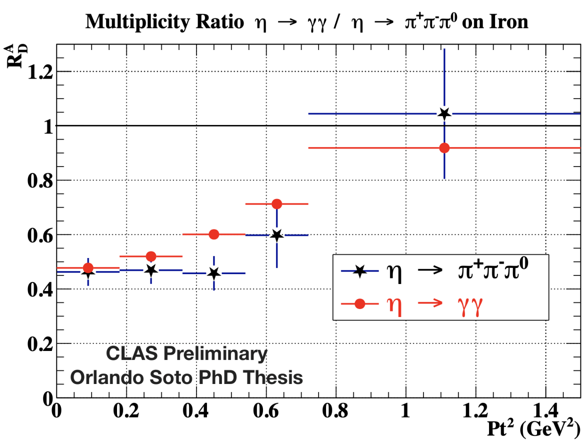

FIG. 7. Multiplicity ratios for eta mesons in two decay channels as a function of p_T^2 from the CLAS 5 GeV data from the EG2 run period. Error bars reflect statistical uncertainties only. For the $\gamma\gamma$ decay channel the error bars are smaller than the points shown.

1. BOSE EINSTEIN CORRELATIONS

With the CLAS 5 GeV data we have developed the technique for Bose-Einstein correlation studies with identical pions produced in SIDIS. Such studies reveal spatial information about the source size of the process that produced them. This is relevant both for the study of the fundamental hadronization process and for understanding more about that process when it occurs in the nuclear medium.

In Figures 8 and 9 are shown some results from that work. One-dimensional and two-dimensional correlation functions have been derived for deuterium, carbon, iron, and lead targets, normalized to mixed events and to simulated events. The two-dimensional correlation functions

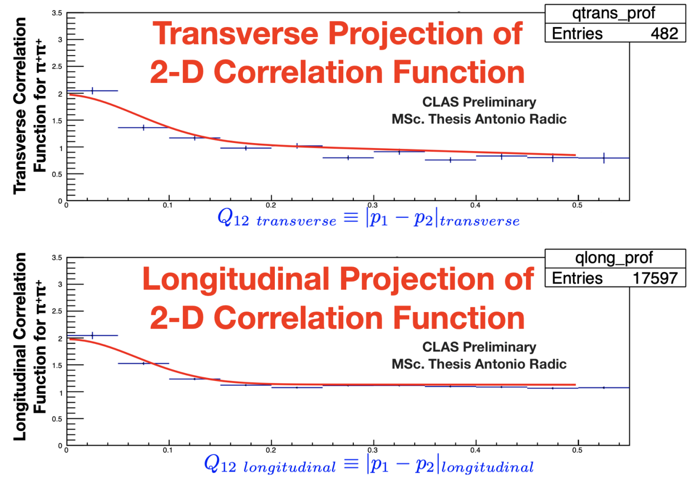

FIG. 8. Results from an analysis of Bose-Einstein Correlations in SIDIS $\pi^+\pi^+$ events, showing longitudinal and transverse projections of a 2-dimensional correlation function for carbon.

quantify the longitudinal and transverse source dimensions, thus permitting a non-spherical source shape. In Fig. 8 are projections of the longitudinal and transverse correlation functions fitted to a conventional modified Goldhaber parameterization. In the upper part of Fig. 9 are shown the longitudinal and transverse sizes found in deuterium, carbon, iron, and lead nuclei. In the lower part of that figure are shown the ratios of transverse size to longitudinal size as a function of nuclear mass number. The pattern seen in this plot is that in deuterium the source is longer than it is wide, but in the larger and larger nuclei it becomes wider and wider, ultimately becoming 50% wider than it is long, due to its interactions over longer nuclear pathlengths. This is qualitatively what one expects from a hadronic or partonic cascade in the medium.

The present study is too limited in statistical precision to go much further with the 5 GeV data. An exploratory study of the z_h^{pair} dependence was attempted, but more data are needed to understand, for example, if the source size is different for the current fragmentation region from the target fragmentation region, and to understand if those sizes are modified in the nuclear medium. This will be the subject of the study in the 12 GeV data.

2. DIQUARK DEGREES OF FREEDOM IN BARYONS

In September 2019 there was a workshop at the ECT* in Trento named "Diquark Correlations in Hadron Physics: Origin, Impact and Evidence.[16]" This workshop stimulated a new line of thinking about the possibilities of studying diquarks with baryon hadronization in nuclei. A document describing the major outcomes of the workshop, including this topic, is in preparation[17]. We describe the idea very briefly here. More information is

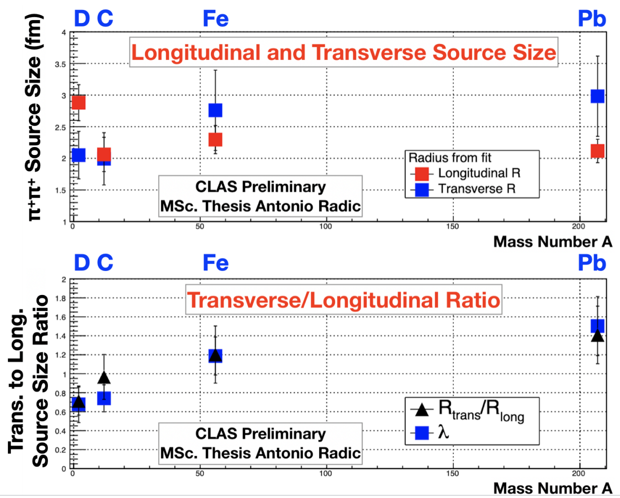

FIG. 9. Results from an analysis of Bose-Einstein Correlations in SIDIS $\pi^+\pi^+$ events, showing source sizes and Transverse/Longitudinal size ratios for deuterium, carbon, iron, and lead nuclei. The ratio of transverse size to longitudinal size increases with mass number A from 0.7 for deuterium to 1.5 for lead, consistent with a transverse spread due to the nuclear medium, such as might be expected for a hadronic or partonic cascade inside the nucleus.

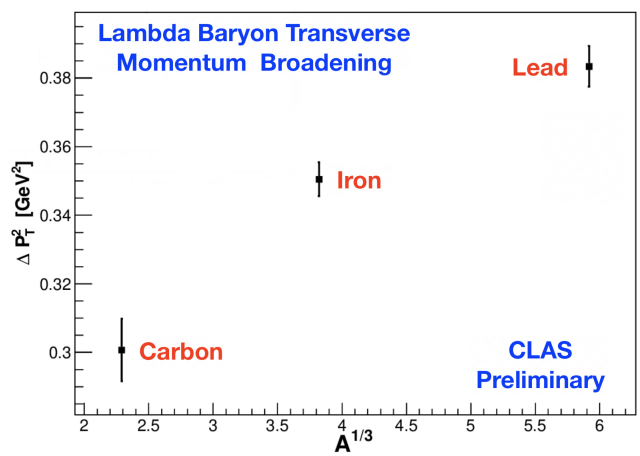

FIG. 10. Preliminary transverse momentum broadening of the lambda baryon from the CLAS 5 GeV data, EG2 run period. The broadening is an order of magnitude larger than what is typically measured for pions in HERMES and CLAS and for positive kaons in HERMES.

available in the ECT* presentation slides on the web.

The HERMES 2D hadronization paper presented multiplicity for charged pions, charged kaons, and proton and anti-proton in neon, krypton, and xenon targets normalized to deuterium. For most of these hadrons, the qualitative behavior of the multiplicity ratios was similar, including that of the antiproton. However, the qualitative behavior was different for the proton multiplicity ratio. The largest value of the multiplicity ratio was more than 2.0 for the proton, larger than for all other hadrons. Also, for the other hadrons, the strong Cronin-like enhancement at high p_T^2 disappears for high z_h (as seen also in the CLAS π^0 data presented above). However, for the proton the high-z_h data also show the Cronin-like enhancement. Finally, the multiplicity ratio for the proton is much greater than 1.0 as a function of ν for low z_h. For all other hadrons it is less than 1.0, rising slowly toward unity as ν increases. In the BL framework this is simply interpreted as the increased Lorentz boost of the single struck quark at high ν, which causes time dilation of the color lifetime and thus a decrease in all modifications due to the nuclear medium; in this picture, the multiplicity ratio cannot be greater than unity when expressed as a function of ν when integrated over all other variables. This interpretation cannot be made for the proton multiplicity ratio.

The qualitatively different behavior of the proton is a puzzle. More evidence to help understand it comes from the 5 GeV CLAS data, in particular in the preliminary hadronization analysis of the lambda baryon. These data show very large enhancements in the multiplicity ratio for lambdas, particularly for low z_h. While still preliminary, the data have been carefully studied and this enhancement appears to be real. What it indicates is that the object traveling through the nucleus interacts very strongly with the medium. In the BL framework it is a single quark, transitioning into a pion, that interacts with the medium, and its attenuation is well-described by the published pion-nucleon cross section. Even more striking is the transverse momentum broadening seen for the lambda, shown in Fig. 10. It is one order of magnitude greater than that of the pions and K^+ studied by HERMES. This is the most powerful single piece of information in these studies. If the initial state consists of a single struck quark, and if the p_T broadening comes (in first approximation) from the multiple scattering of that quark, then the p_T broadening for the lambda should be similar to that seen for the pions and positive kaon of HERMES. The simple experimental explanation for these observations is that the struck object is sometimes not a single quark, but a diquark. A colored diquark moving through the nuclear medium will experience much more transverse momentum broadening because it has a much larger color field. In what follows this will be referred to as direct diquark scattering (DDS).

So far, the DDS idea could be seen as speculation. There is more information from CLAS at 5 GeV on the proton observables which support the DDS idea, but information from protons can always be questioned because there are protons in the nucleus in the initial state which could get knocked out in some multi-step process. Alternative explanations to DDS might be that the lambda is formed much more quickly than the pion (although unlikely for a larger, heavier system), and multiple-scatters as a hadron in the medium. It would be much more convincing to have a series of observations that require DDS as an explanation.

The DDS idea must be tested experimentally and validated theoretically before it can eventually be accepted. There is an ideal path to accomplish this, and it consists of the baryon hadronization program that has been part of our 12 GeV experiment from the beginning. The theoretical backdrop comes from studies of diquark correlations in sophisticated theoretical models. A recent effort with the Dyson-Schwinger equations produced masses of ground-state mesons and baryons, including those with heavy quarks, for 19 different mesons and 24 baryons [26]. In solving for the spectrum of ground state baryons, a quark-diquark approximation to the Faddeev equation was used, and thus the starting point was to compute the properties of diquark correlations. In this work they found diquark masses of 0.77 GeV and 1.06 GeV for ud and uu diquarks, respectively; comparable to the proton mass.

In Table I is a list of the baryons for uds systems and their dominant quark-diquark component according to this work. As can be seen, the neutron, proton, and lambda have in common the [ud] diquark, while the sigma and xi have [us] as the dominant diquark, and the antinucleons have antiquark diquarks. This, together with the hypothesis of DDS, suggests a qualitative prediction. If DDS is possible, then the hadronization observables of the proton, neutron, and lambda will be the same (up to mass effects) and the hadronization observables of the sigma and xi baryon, antinucleons, and higher mass baryons, will be different. In this picture, the diquark is knocked out of the proton or neutron in the nucleus, and forms a new proton or neutron or lambda with only a single string break needed (in the LSM terminology). For those events, the traveling object is a diquark, and very large multiplicity ratios and p_T broadening will be observed. For other events, a single quark from the proton or neutron is struck and travels through the medium, just as in the case of the pion production. The p_T broadening should then be very similar to that of the pion, and the multiplicity ratio will be qualitatively similar to that of the pion or kaon or antiproton, aside from small mass effects.

Needless to say, if the quark-diquark structure of the nucleon can be definitively established through measurements such as the above, it would have a strong impact on our understanding of proton structure. This could take the form of characterizing diquark properties through the kinematic dependences on ν, Q^2, z_h, x_{Bj}, and p_T of hadronization observables for the baryons that contain specific dominant diquark configurations.

3. DIQUARK DEGREES OF FREEDOM IN BARYONS FROM DIHADRON STUDIES

If diquarks explain the hadronization patterns of baryons as discussed above, then it means that direct diquark scattering (DDS) can occur. In that case there will be two categories of events, depending on whether the diquark remains intact or whether it breaks up via interaction with the medium or in subsequent fragmentation stages. The intact diquarks will be associated with the production of [ud]x baryons like the proton and the lambda. The diquarks that break up will be likely to form dihadrons, with di-pions being the most probable.

TABLE I. Table of baryons and their dominant diquark correlation components according to reference [26]. Adapted from Table IV of that work.

Baryon	Dominant Correlation
p	$[ud]u$
$\bar{p}$	$[\bar{u}\bar{d}]\bar{u}$
n	$[ud]d$
$\bar{n}$	$[\bar{u}\bar{d}]\bar{d}$
Λ	$[ud]s$
Σ	$[us]u$
Ξ	$[us]s$

There would be several possible indications of DDS in di-pion events. First, they would be characterized by somewhat larger transverse momentum broadening because the diquark could be intact for part of its path through the medium, and as argued above, that produces a much larger colored object in the medium than a single quark. Second, one can compare di-pion transverse momentum broadening with di-kaon transverse momentum broadening, because di-kaons cannot be easily produced by DDS on [ud]x baryons like the proton and the neutron. Thus the transverse momentum broadening of di-kaons should be smaller than that of di-pions if DDS is prevalent. Finally, if diquarks are large colored objects, the Q^2 dependence of di-pion production should be significantly different from di-kaons and single high-z_h pion production because of the resolving power of the virtual photon, $1/Q$.

With the 12 GeV data and the high acceptance and good PID of CLAS12 we will have an opportunity to study this in great detail. We can see hints of this even in the 5 GeV data, as seen in Fig. 11. In that figure on the left is shown the distribution of identified positive pions. As can be seen, there are many events in which more than one positive pion is measured. This opens up the possibilities for many types of measurements, particularly correlation measurements. A separate proposal is planned to be submitted by M. Arratia that fully develops this theme. A simple transverse momentum broadening plot is shown for one, two, and three pion events. These data have no kinematic cuts except $Q^2 > 1$ GeV^2 and $W > 2$ GeV, so the broadening is averaged over, for example, z_h. Larger broadening numbers emerge for more specific kinematics, which may allow more precise interpretation in terms of physics information such as pathlength in the medium, diquark degrees of freedom, etc. Such multi-pion final states will also be of high value in studying the fragmentation characteristics of sub-leading hadrons. Multiplicity ratios and transverse momentum broadening can be developed for leading hadrons and for several subleading hadrons, and the result can be fitted by an extension of the BL framework and compared to the Lund String Model and to other model predictions.

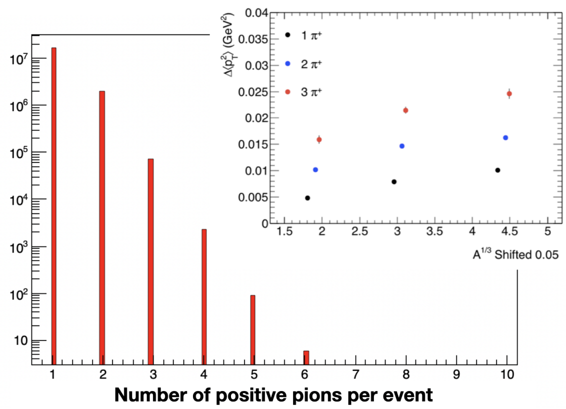

FIG. 11. (left) Number of identified positive pions per event seen in the CLAS 5 GeV data. (upper right inset) Preliminary one-dimensional transverse momentum broadening of positively charged pions from the CLAS 5 GeV data, EG2 run period. The broadening is shown for events with one positive pion, two positive pions, and three positive pions. No corrections have been applied for the data shown in the figure. It is anticipated that with the 12 GeV data we will probe even further into the space of multiple identified hadron events due to greater luminosity, increased phase space, and better particle identification for strange particles. This will allow study of multiparticle hadron correlations, the beginnings of jet-like behavior, and mesons that decay into many-particle final states such as the f1 meson. Such multi-pion final states will also be of high value in studying the characteristics of sub-leading hadrons from the fragmentation process.

II. STATUS OF EXPERIMENT PREPARATION

The experiment uses the standard CLAS12 setup except for the target assembly. The 5 GeV experiment used a dual target where the deuterium cryotarget was mounted just upstream of the solid target, so that the same beam passed through both[10]. This arrangement reduces systematic uncertainties in most observables, particularly for time-varying effects such as inoperative detector channels. A new version of this target has been designed and built in Chile. It is much lower in mass and can accommodate more solid targets than the six that were possible with the previous one (the limit was due to CLAS having six torus coils). It has been presented at two experimental readiness reviews, and in response to questions from one of those it has been subjected to extended radiation testing in a monitored radiation area in Hall A. No problems have been found with it.

III. SUMMARY

This experiment will break new ground in several key areas. It has important links to related measurements at the future EIC, but will have much higher luminosity so as to be able to explore the rarer channels, such as phi, eta-prime and f1 meson production, whose formation characteristics are completely unknown. It is strongly connected to worldwide studies on jet quenching in hot dense matter in that it would advance the basic validation of the current formalisms of quark energy loss and related topics. Concerning possible diquark degrees of freedom it is very strongly connected to baryon structure. In the thrust of determining fundamental properties of hadronization, including hadronization mechanisms and characteristics of leading and subleading hadrons, it is connected to every high energy experiment that creates new hadrons. We urge the PAC to reaffirm the high importance of this experiment and to maintain the requested number of PAC days at 60 as originally approved.

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