Update on E12-06-107: Hadron Propagation and Color Transparency at 12 GeV

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Executive Summary

The A(e,e'p) proton knockout portion of this experiment, to measure the proton nuclear transparency, successfully ran as one of Hall C commissioning experiments in 2018. This part of the experiment corresponded to 211 approved hours or 8.5 PAC days, out of the total 26 PAC days approved for E12-06-107. The preliminary results on the proton nuclear transparency in ^{12}C nuclei over the range Q^2 = 8 - 14.3 (GeV/c)^2 were presented at the recent APS meeting in Denver. The lack of any enhancement in transparency as observed in our results led to lively discussion on the impact of these data, and rapid follow-up from theory colleagues.

We request the remaining 17.5 PAC days of beamtime to complete the experiment by measuring the A(e,e'π^+) pion electroproduction cross sections to extract the pion nuclear transparencies in the nuclear medium. The pion (π^+) transparency measurements will be performed on ^{1}H, ^{2}H, ^{12}C, and ^{63}Cu, over the range Q^2 = 5 - 9.5 (GeV/c)^2. Given the less-known reaction mechanism of the pion, it is essential to map *both* the Q^2- and A-dependence, and a minimum of two heavy target nuclei is required.

Measurements of proton and pion transparencies are fundamental in their own right, as they shed light on the propagation of protons and pions in nuclear matter, which is important for the interpretation of many experiments and phenomena. Further, a rise in the proton and pion transparency as a function of Q^2 is predicted to be a signature of the onset of Color Transparency. Mapping the onset of any Color Transparency effects, uniquely points to the role of color in exclusive high-Q^2 processes.

No evidence of an energy dependence of transparency has been found in A(e,e'p) experiments to date, including the preliminary results from the completed part of this experiment. These results are at odds with the increase in the nuclear transparency reported by a BNL experiment for the A(p,2p) reaction, at similar proton momentum range (up to 8.5 GeV/c). However, onset of Color Transparency effects were reported at $Q^2 \sim$ 1-2 GeV/c in pion

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electro-production from nuclei. This is further corroborated by a ρ^0 production measurements at JLab. The occurrence of such effects in meson electroproduction experiments is an effective signature of the approach to the factorization regime, necessary for the access to Generalized Parton Distributions through high-Q^2 deep exclusive processes.

The proposed experiment seeks to measure the pion transparency up to the highest Q^2 that can easily be reached at the 12-GeV JLab, using the HMS and SHMS spectrometers. Pion and proton transparencies provide a natural meeting ground between experiment and meson-nucleon as well as QCD inspired calculations of the propagation of highly energetic particles through the nuclear medium, which remains a very active area of study. The pion transparency measurements will uniquely confirm the onset of Color Transparency in mesons that was observed in the 6 GeV experiments and map the phenomenon up to $Q^2 \simeq 10$ (GeV/c)^2. We request the remainder of the 17.5 PAC days with beam currents of up to 80μA that were approved for experiment E12-06-107. The beam will be used to measure the exclusive A(e,e$'\pi^+$) reaction and map the Q^2 and $A-$dependence of pion transparency up to $Q^2 \approx 10$ (GeV/c)^2, off the nuclei ^{12}C and ^{63}Cu, with ^{2}H as the calibration nucleus.

1 Physics Motivation

1.1 Overview

The quarks and gluons of QCD are hidden. Protons and neutrons that are the constituents of nuclei are identified with color singlet states and have strong interactions very different from that of the gluon exchange by colored quarks and gluons. Protons and neutrons rather seem bound together by the exchange of evanescent mesons. Hence, at low energies or long distances the nucleon-meson picture in the standard model of nuclear physics is very successful in describing the overall features of the strong interaction. Nonetheless, at sufficiently high energies or short distances perturbative QCD (pQCD) with its quark-gluon degrees of freedom must allow for extremely precise description of nuclei. The study of the transition between these regimes, transcending from the hadronic degrees of freedom to the partonic degrees of freedom is an important goal in intermediate energy nuclear and particle physics.

The availability of high-energy beams provides the opportunity to search for the presence of QCD as the ultimate source of the strong interaction. In particular, exclusive and semi-exclusive processes are essential in studies of the role of color in high-momentum transfer processes. This is because manifestation of the underlying quark-gluon degrees of freedom of QCD naturally gives rise to a distinct set of phenomena in exclusive processes on nucleons and nuclei. A popular method, then, used to explore the transition region is to look for the onset of any phenomena related to color degrees of freedom deviating from conventional nucleon-meson pictures. One such fundamental prediction of QCD is the phenomenon of Color Transparency (CT), that refers to the vanishing of the final (and initial) state interactions of hadrons with the nuclear medium in exclusive processes at high momentum transfer [1].

The propagation of hadrons in the nuclear medium is an essential element of the nuclear many body problem, and beyond CT, the attenuation of hadrons propagating through the nuclear medium are driven by more ordinary absorption mechanisms. At high hadron energies, the main process of concern is the reduction of the hadron flux. This reduction factor is called nuclear transparency T. For hadron momenta larger than 1 GeV/c, where the inelastic part of the free hadron-nucleon cross sections dominates, Glauber-type calculations are often used to calculate the nuclear transparencies. Because understanding of the propagation of hadrons in nuclear matter is important for the interpretation and understanding of many phenomena and experiments, such calculations remain an active area of interest. Moreover, nuclear transparency can also be used to search for signature of Color Transparency.

The concept of Color Transparency (CT) was introduced almost four decades ago by Mueller and Brodsky [1]. The basic idea is that, under the right conditions (such as sufficiently high momentum transfer), three quarks, each of which would normally interact very strongly with nuclear matter, could form an object of reduced transverse size, (i.e. scattering takes place via selection of amplitudes in the initial and final state hadrons characterized by a small transverse size). Secondly, this small object should be 'color neutral' outside of this small radius in order not to radiate gluons. Finally, this compact size must be maintained for some distance in traversing the nuclear medium, so that it passes undisturbed through the nuclear medium. As a result, the measured nuclear transparencies would increase with energy.

Nuclear transparency defined as the ratio of the cross section per nucleon for a process on a bound nucleon in the nucleus to the cross section for the process on a free nucleon, is the commonly used observable in searches for this phenomena. A clear signature for the onset of CT would involve a dramatic rise in the nuclear transparency as a function of momentum transfer involved in the process, i.e. a positive slope with respect to the momentum transfer.

More recently, CT has also been discussed in the context of QCD factorization theorems which are intrinsically related to the access to Generalized Parton Distributions (GPD's) [2, 3]. Experimental access to such GPD's is amongst the highest priorities in intermediate energy nuclear/particle physics. It is still uncertain at which Q^2 value one will reach the factorization regime, where leading-order perturbative QCD is fully applicable. During meson electroproduction, upon absorbing the virtual photon the meson and the baryon move fast in opposite directions. It has been suggested [4] that the outgoing meson maintains a small transverse size which results in a suppression of soft interactions (multiple gluon exchange) between the meson-baryon systems moving fast in opposite directions and thereby leading to factorization. Consequently, factorization is rigorously not possible without the onset of the Color Transparency (CT) phenomenon [4]. The underlying assumption here is that in exclusive "quasielastic" hadron production the hadron is produced at small interquark distances. However, just the onset of CT is not enough, because quark transverse momentum contributions can be large at lower Q^2s which could lead to breakdown of factorization. Thus it is critical to observe the onset of CT in hadron production as a precondition to the validity of factorization. Furthermore, several authors have formally identified such connection between GPDs and CT [5, 6]. These theoretical works illustrate the important link between GPDs and CT and provides additional motivation for the clear and unambiguous establishment of CT phenomena.

For the most recent review of the CT phenomenon see Ref. [7].

1.2 Previous Measurements

1.2.1 Proton Knockout Experiment

The A(e,e'p) portion of E12-06-107 (this experiment) was carried out as one of the Hall C commissioning experiments. Data were collected over a Q^2 range of 8 - 14.3 (GeV/c)^2, which included one point which overlaps with the highest Q^2 point from the previous JLab 6 GeV experiment. This experiment reached the highest Q^2 reached by any A(e,e'p) experiment. Two students are analyzing the data as part of their thesis and the analysis is progressing rapidly. Preliminary results from this experiment were presented in an invited talk at the APS topical group on Hadronic Physics in April 2019. Fig. 1 shows the preliminary results along with all previous measurements. The preliminary results seem to exclude sizable CT effects up to $Q^2 = 14.3$ (GeV/c)^2. This lack of an onset of CT at these significantly high Q^2 is a serious challenge for theory. Note that this Q^2 range corresponds to proton momenta up to 8.5 GeV/c, and thus the lack of enhancement of the transparency is at direct odds with the reported rise (and fall) of nuclear transparency extracted from BNL/AGS A(p,2p) data. Final results and a publication is expected to be completed in the Fall.

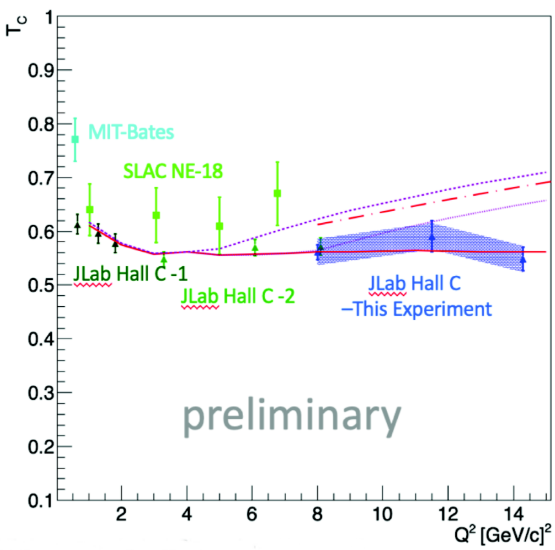

Figure 1: Nuclear transparency as a function of Q^2, for ^{12}C. The preliminary results from E12-06-17 (this experiment) along with all the previous experiments at Bates, SLAC, and JLab are shown. The solid line (red) is the prediction of the Glauber approximation [8]. Also shown are the predictions of several CT calculation, dashed blue lines are for CT added to a Glauber calculation [9] for two different set of parameters and dashed red line is for CT added to a relativistic Glauber calculation. [10].

1.2.2 Meson Production Experiments

Intuitively, one expects an earlier onset of CT for meson production than for hard proton scattering, as it is much more probable to produce a small transverse size in a $q\bar{q}$ system than in a three quark system [11]. Moreover the evolution distances (formation length) are easily larger than the nuclear radius even at moderate Q^2 (the evolution time is dilated by a factor E/M in the frame of the fast moving small transverse size object, with E and M being the the energy and mass of the pion). This increases the chances of the small transverse size object to pass undisturbed through the nucleus.

Experiments performed at Fermilab, DESY and JLab seem to support this idea [12–14]. One such experiment is the Fermilab experiment on coherent diffractive dissociation of 500 GeV/c negative pions into di-jets [12]. The inferred

Q^2 for this reaction was ≥ 7 (GeV/c)^2. The A-dependence of the data was fit assuming $\sigma \propto A^\alpha$ The alpha values were determined to be $\alpha \sim 1.6$, far larger than the $\sigma \propto A^{0.7}$ dependence typically observed in inclusive π-nucleus scattering, and the experimental results were consistent with the predicted theoretical [15] values that include CT. The authors of this experiment consider the data to have conclusively shown full CT for pions at these high momentum transfers. Of course, these data do not inform about the kinematic onset of CT.

The two most recent experiments in search of CT, were also performed at JLab. In the first experiment the A(e,e'π^+) process on ^{1}H, ^{2}H, ^{12}C, ^{26}Al, ^{64}Cu and ^{197}Au (E01107) was used to measure the pion transparency over a Q^2 range of $1-5$ (GeV/c)^2 [16]. The second experiment studied the A(e,e'ρ^0) process on ^{1}H, ^{2}H, ^{12}C, and ^{56}Fe targets over a Q^2 range of $1-3$ (GeV/c)^2 [17]. The nuclear transparency is extracted in these experiment by comparing the meson production from heavy nuclei to that from hydrogen/deuterium.

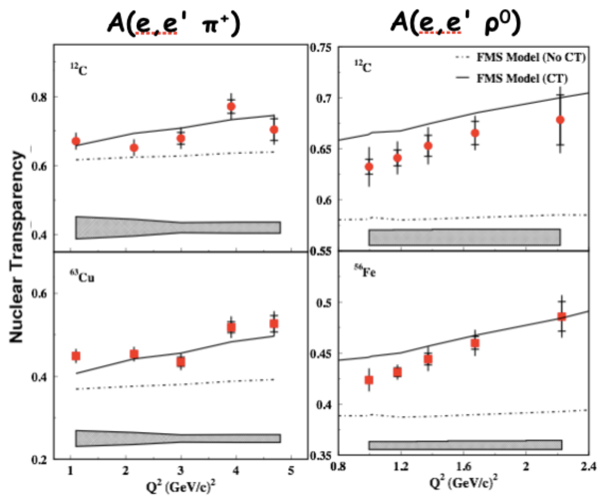

Figure 2: Nuclear transparency as a function of Q^2, for A(e,e'π) reaction on ^{12}C and ^{63}Cu (left) and for A(e,e'ρ^0) reaction on ^{12}C and ^{56}Fe. The solid line in all the plots is a calculation that includes CT [18] while the dot-dashed line is a which does not include CT. The systematic uncertainty for each measurement is shown as a gray band. These results are seen as conclusive demonstration of the onset of CT for mesons in the few GeV energy range.

The kinematics of E01107, $\vec{p}_\pi \| \vec{q}$, were chosen to minimizes contribution of the elastic rescattering. The coherent length defined as the distance between the point where γ^* converted to a $q\bar{q}$ and the interaction point -$l_c = 2q_0/(Q^2 + M^2_{q\bar{q}})$ is small (0.2 - 0.5 fm) for the kinematics of E01107 [16, 19] and varies weakly with Q^2 (making it essentially constant and very small). This removes any coherence length dependence of the transparency through t-channel $\pi-\rho$ exchange and simplifies interpretation of the Q^2 dependence of the transparency. This is one of the key advantages of pion electroproduction in the search for onset of CT. In the A(e,e'ρ^0) process, however, a coherence length dependence of the transparency, where the nuclear transparency decreases with an increase of the coherent length, can mimic a CT-like energy dependence. To mitigate this effect the JLab A(e,e'ρ^0) experiment was performed at fixed coherence length.

The pion electroproduction experiment, E01107 was the first JLab experiment to report evidence for the onset of CT [16] in the process $eA \rightarrow e\pi^+ A^*$. The measured pion nuclear transparency (as compared both to hydrogen and deuterium cross sections) show a slow but steady rise versus pion momentum for the nuclear ($A > 2$) targets. An increase in transparency both as a function of pion momentum (or Q^2) and A was observed, showing a clear onset of a CT-like effect above Q^2 of 1 (GeV/c)^2. These results were covered by physical review focus [20], demonstrating the wide interest in the physics of hadron propagation in general and CT in particular.

Later, the results from the A(e,e'ρ^0) experiment at JLab also confirm the early onset of CT in mesons [17]. To interpret this experiment one needs to take into account the effect of absorption due to decays of ρ^0 to two pions inside the nucleus, and the elastic rescattering contribution which is more important in this case than in the pion experiment since the data are integrated over a large range of the transverse momenta of the ρ meson [18]. Up to these effects, we expect similar transparency for this reaction and for π-meson production. The pion electroproduction and rho experiments together conclusively demonstrate the onset of CT in the few GeV energy range. The results from these two experiments are shown in. Fig. 2

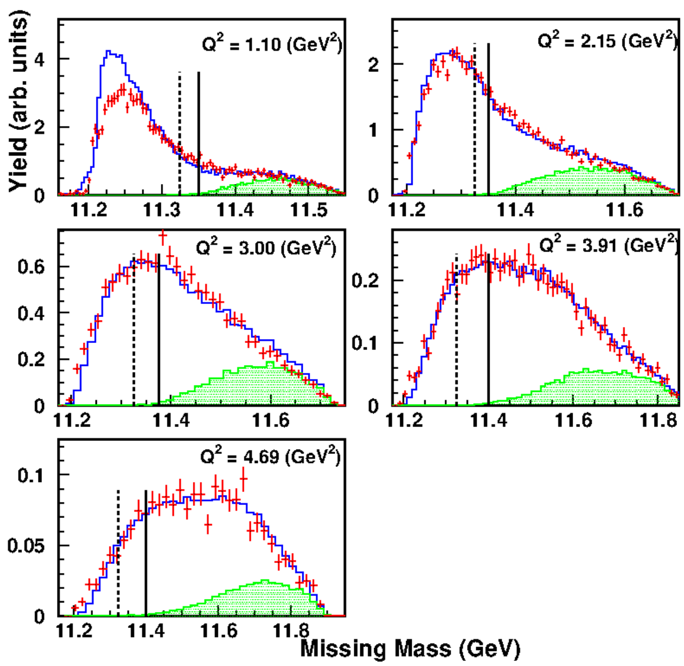

Figure 3: Nuclear missing mass distributions (in GeV^2) for ^{12}C(e,e$'\pi^+$). The data (red crosses) are compared to the simulation (blue line), which is a sum of single-pion and multiple-pion simulations. The shaded areas (green) shows the contributions from the multi-pion simulation. The full simulation is normalized to the data. The dashed vertical lines represents the threshold for double-pion production (11.34 GeV^2). The solid lines represent the position of the cut used in this analysis.

The proposed experiment includes a detailed study of the A(e,$e'\pi$) process. The A(e,$e'\pi$) study would be an extension of the 6 GeV experiment (E01107) to 11 GeV energies. Below we describe some of the results and conclusions of the 6 GeV pion transparency experiment in order to motivate the feasibility of this technique and the need for an extension to higher energies.

The pion transparency experiment E01107 ran in 2004 and collected data on a hydrogen target and four other heavy targets (^{2}H, ^{12}C, ^{63}Cu and ^{197}Au) over a Q^2 range of 1 - 4.7 GeV^2. A PWIA simulation of this experiment reproduced the shapes of the W, Q^2 and $|t|$ distributions reasonably well [16, 19]. The good agreement between the data and the Monte Carlo simulation was typical for all targets and over the entire Q^2 range. This gives us confidence in the experimental technique for extracting nuclear transparency from A(e,e'π^+) measurements. Over most of the kinematics covered in the 6 GeV experiment, single pion production dominates. The production of more than one pion in a single event (multiple pion production) was suppressed for hydrogen target during the pionCT experiment due to the relatively high $Q^2 > 1$ GeV^2 and W >2.1 GeV above the resonance region. For targets with $A > 1$, multiple-pion events can only be produced above a missing mass threshold that is larger than the missing mass threshold for single-pion production, i.e. $M_x = M_{A-1} + M_\pi$ for a nucleus of mass A. In order to describe events above the two pion threshold, a multiple-pion production simulation was developed for the nuclear target analysis. The mechanism for multiple-pion production was assumed to be quasi-free single-pion production from a nucleon followed by a secondary process that was incoherent from the first, where the pion produced one or more pions from a different nucleon. The cross section for the secondary process was assumed to be uniform over the acceptance of the HMS spectrometer. The effect of multi-pion production can be seen in Figs. 3 for the carbon target, which show that the multi-pion production yield above threshold is clearly identifiable even at the highest Q^2. The agreement between the missing mass distributions obtained from data and simulation is excellent at high Q^2. The discrepancy seen at Q^2= 1 GeV^2 is attributed to the reaction mechanisms missing from the simulation, such as final state interactions between the knocked-out neutron and the residual nucleons (nN-FSI) and short range correlations. The effect of these reaction mechanisms decrease with increasing Q^2. These results show that it is safe to increase the double-pion missing mass cut above the threshold with minimal contamination. The double-pion missing mass cut was placed at the position where the systematic uncertainty from the contribution of multiple-pion events was less than 5%. With these cuts, the total uncertainty due to multi-pion contamination is <0.4%. We also noted an interesting smooth A dependence in the ratio of the multiple-pion to single-pion yields.

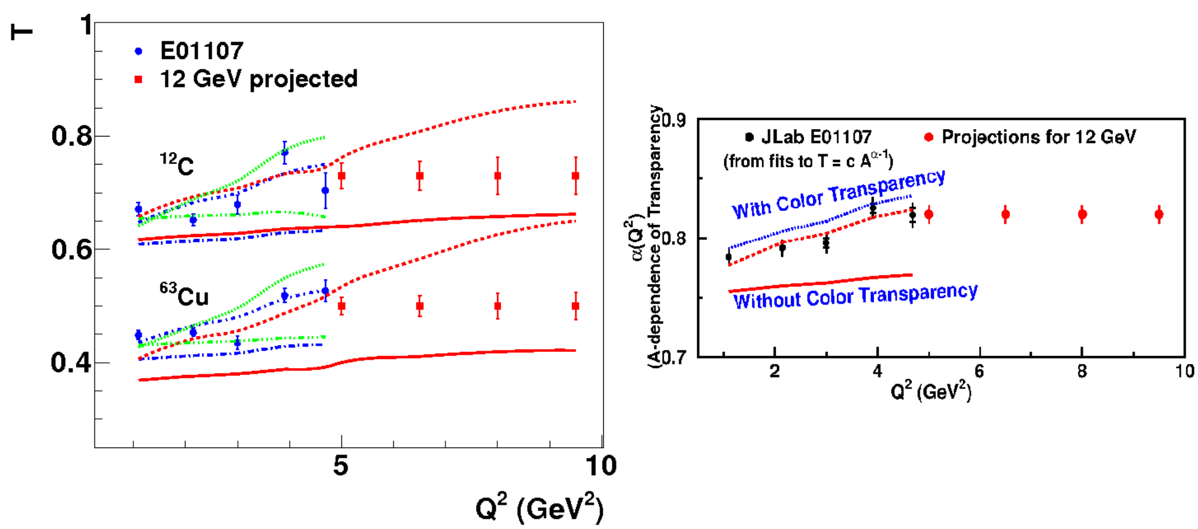

Figure 4: (left) The projected results for A(e,e'π) along with results from E01107. The error bars represent only the statistical uncertainty. All the available calculations are shown along with the projections of Cosyn *et. al* [25]. (right) The projected results for A(e,e'π) along with the results from from E01-107. The error bars represent the quadrature sum of the statistical and the a 5% systematic uncertainty. The calculations are same as the left panel.

The two JLab experiments (π and ρ^0 transparency), together with the previous meson transparency measurements [12, 21], suggest a gradual transition to meson production with small inter-quark separation, and the onset of reaction mechanisms necessary for QCD-factorization at Q^2 values of a few (GeV/c)^2. These results also put severe constraints on early models of CT which predict a dramatic transition with a threshold-like behavior. We prefer to view the low-Q^2 data from the E01-107 experiment to provide the first reliable "baseline" for this process.

The CT effects can be unambiguously verified only as a deviation from a baseline nuclear physics calculation. A Q^2 dependence of the pion transparency in nuclei may also be introduced by conventional nuclear physics effects at the lower Q^2s. Thus one must simultaneously examine both the Q^2 and the A dependence of the meson transparency. Several independent calculations [22,23] predict the CT effect to be largest around Q^2 of 10 (GeV/c)^2, which is in agreement with the observation of full CT in the Fermilab experiment mentioned above. Note that an extension of the ρ^0 transparency experiment to 11 GeV has also been approved, however, that experiment would extends the ρ^0 measurements only up to Q^2 of 5.5 (GeV/c)^2 [24]. On the other hand, using a 11 GeV beam one can extend the (e,e'π^+) measurement on nuclear targets to Q^2 of 10 (GeV/c)^2. Both experiments are important to map out the CT phenomena in mesons. Using the data collected at 6 GeV as a baseline, the new data could help confirm and help establish the CT phenomena in mesons on a firm footing. The projected results are shown in Fig. 4, along with results from the previous A(e,e$'\pi^+$) experiments.

1.3 Beam Time Estimate

Q^2 (GeV/c)^2	Uncertainty %	^{1}H Run time (hours)	^{2}H Run time (hours)	^{12}C Run time (hours)	^{63}Cu Run time (hours)	Run time (total)
5.0	1	2x3	2	2.5+6	10	26.5
6.5	2	2.5x3	2.5	3+7	12.5	32.5
8.0	3	5x2	5	6	25	46.0
9.5	3	34x2	34	41	170.0	313.0
				Total		418

Table 1: Run time and statistical uncertainty for the (e,e'π) process. The additional time for the ^{1}H target is to cover larger θ_{pq} around the parallel kinematics. The additional time on the ^{12}C target at the lowest 2 Q^2 points is on a 2.5% radiation length target and will be used to test the radiative correction procedure.

1.4 Summary

The A(e,e$'$p) process was successfully measured as a commissioning experiment and the preliminary results seem to rule out large CT effects. The completion of this approved 12-GeV experiment E12-06-107 with the collection of the A(e,e$'\pi^+$) data will allow:

1. Measurements of pion transparencies to allow understanding of the propagation of highly-energetic pions through nuclear matter.

2. The A(e,e$'\pi^+$) process can map the region from the onset of Color Transparency towards the region in Q^2, expected to be $\simeq$ 10 (GeV/c)^2, where such effects validate the strict applicability of factorization theorems for meson electroproduction experiments.

The experiment will measure the A(e,e$'\pi^+$) cross section on ^{1}H, ^{2}H, ^{12}C and ^{63}Cu over a Q^2 range of 5 - 9.5 (GeV/c)^2. A total of 418 hours, or 17.5 PAC days, of the original approved 26 PAC days for E12-06-107 is required for this part of the experiment, as further detailed in Table 1. This maps the pion nuclear transparency over a region bridging where earlier 6-GeV experiments noted a rise in transparency to the Q^2 region where the Fermilab di-jet results were interpreted as signature of full Color Transparency. The projected results are shown in Fig. 4, along with results from the previous A(e,e$'\pi^+$) experiments.

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