Proposal for PAC48: "Dihadron measurements in electron-nucleus scattering with CLAS12"

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Abstract

We propose a new CLAS12 program based on studies of dihadron angular correlations in nuclear DIS, which have never been measured before. This proposal builds on the recently observed suppression of back-to-back pion pairs in CLAS6 data, which hints novel nuclear effects. The increase in beam energy and improved instrumentation will allow us to elucidate the nature of this effect. These measurements will also be complementary to the future EIC, as the high acceptance of CLAS12 makes it uniquely suited to cover a kinematic range that is difficult to access in collider mode but crucial for a full understanding of QCD in nuclei.

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I. INTRODUCTION

The proposal consists of a series of measurements of dihadron azimuthal correlations in DIS off nuclei, which aim at constraining "cold nuclear matter" effects. These type of measurements, which have never been done, will illuminate aspects of hadron production in nuclei that cannot be probed with single-hadron measurements. This proposal also represents a path-finder for the EIC, which complements similar endeavours at RHIC [1]. This proposal seeks an addition to Run Group E with the aim to complement the "Quark Propagation and Hadron Formation" experiment number E12-06-117. Given the open-trigger nature of CLAS12, no changes to the experimental setup, beam conditions, or beam time are requested.

A. Motivation

The study of cold-nuclear matter effects illuminates emergent QCD dynamics in nuclei. The existing data of hadron production in electron-nucleus DIS (EMC, HERMES, CLAS and others) agree with several models that include either gluon bremsstrahlung, "pre-hadron" states, intranuclear re-scattering of hadrons and absorption, or a mixture of these [2–31]. More detailed studies are needed to elucidate the relative weight of these effects and to extract key parameters such as the hadron formation time or transport parameters of nuclei [32].

A key target in the field is the extraction of $\hat{q}$, which is a transport parameter that describes transverse-momentum broadening due to multiple scattering. A recent analysis by Ru et al. [5] extracted the kinematic dependence of $\hat{q}$ with a global fit to transverse-momentum broadening data from SIDIS (HERMES), Drell-Yan (E772, NA10) and quarkonia production in proton-nucleus collisions (E772, E866, PHENIX, ALICE). As shown in Figure 1, they find a weak Q^2 dependence and a non-trivial dependence on x.

The existing SIDIS data (HERMES) stops at about $x = 0.4$ and has large statistical uncertainties beyond $x = 0.25$. The kinematic coverage for CLAS12 with 11 GeV beam is shown on the right panel of Figure 1. The high-statistics 11 GeV data would probe uncharted kinematics and constrain threshold effects [33], as well as power corrections [34]. As detailed below, we propose to perform

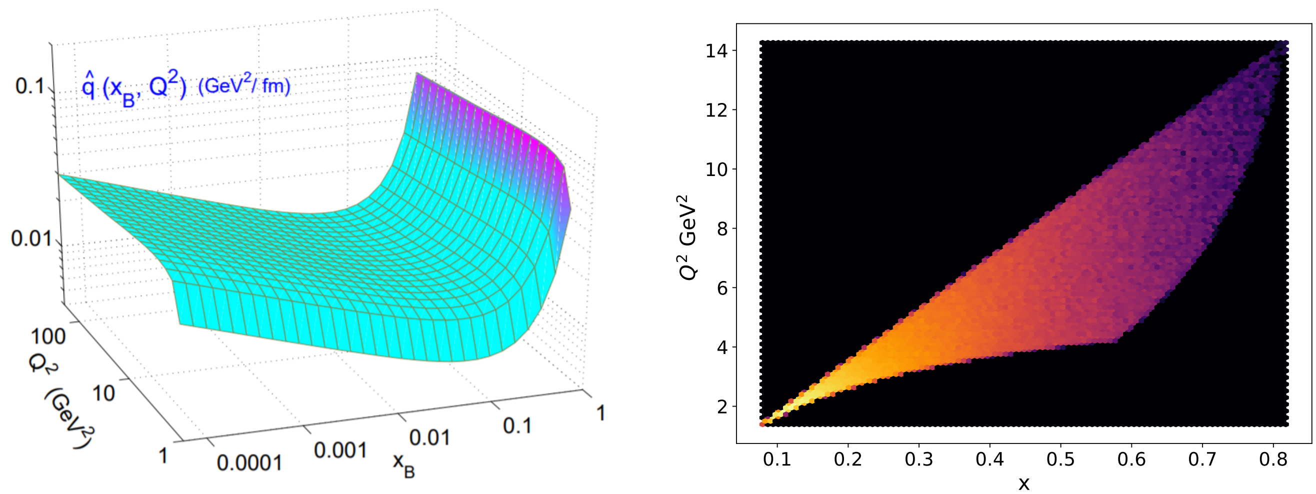

Figure 1. Left: Transport parameter coefficient $\hat{q}$ extracted by Ru et al. [5] from a global fit to SIDIS, Drell-Yan and quarkonia production in proton-nucleus collisions. Right: Kinematic coverage for 11 GeV beam subject to CLAS12 acceptance, and the following selection: $W > 2$ GeV and $y < 0.85$ and at least one hadron with $z > 0.4$.

dihadron azimuthal measurements. Broadening of dihadron correlations probe multiple-scattering in nuclei with greater sensitivity than single-hadron measurements [35].

Azimuthal correlations between pairs of hadrons produced in high-energy nuclear collisions played a pivotal role in the quest to study the quark-gluon plasma [36, 37]. A strong suppression of back-to-back pairs represented first evidence of the “jet quenching” phenomena. Similar measurements have been performed in hadron-nucleus collisions at collider (e.g. Ref. [38]) and fixed-target experiments (e.g. Ref. [39]) to study cold-nuclear-matter effects. No analogous study has been carried out in DIS. These type of studies could illuminate the role of nuclear geometry and spatio-temporal correlations in nuclear DIS.

Furthermore, dihadron production in DIS off nuclei will be one of the main channels for the search of gluon saturation at the EIC [40]. The extraction of a gluon-saturation signal will rely on the calibration of cold-nuclear-matter effects. While there are ways one could gauge the cold-nuclear-matter effects with control regions in future EIC data [41], measurements at JLab can provide crucial checks. The gluon-saturation search at the EIC will cover a kinematic region in Q^2 and y that can be probed with CLAS12, but cover much lower values of Bjorken x given the higher center-of-mass energy. Within QCD factorization, (dihadron) fragmentation functions do not depend on x, so CLAS measurements could constrain them. As shown Figure 1, the expected x-dependence of $\hat{q}$ is rather weak so measurements at $x = 0.1$ could help constrain the $x = 0.01 - 0.001$ region. Moreover, given that the EIC measurements will be performed at $Q^2 \approx 1$ GeV^2, CLAS12 measurements could also help test the applicability of QCD factorization in this region.

Finally, nuclear effects in hadron production also illuminate neutrino-oscillation experiments [42] such as the future DUNE [43], for which multi-pion production in DIS off argon dominates the total cross-section [44]. We seek to compare the studies presented in this proposal with the GiBUU Monte Carlo, which is one of the leading generators used in neutrino oscillation experiments [44].

B. Previous studies

Previous studies focused on the multiplicity ratio, which is defined as the ratio of the number of hadrons per electron DIS off nuclei and deuterium: $R_h = (N_h/N_e)|_A/(N_h/N_e)|_D$. Measurements of R_h for identified hadrons were reported by the HERMES [45–49], and CLAS [50] experiments.

We propose to perform di-hadron measurements, which can be studied with the conditional modification factor, R_{2h} defined as:

$$R_{2h}(z_2) = \frac{N_h^A(z_2|z_1 > 0.5)/N_h^A(z_1 > 0.5)}{N_h^D(z_2|z_1 > 0.5)/N_h^D(z_1 > 0.5)}. \tag{1}$$

Here $z = E_h/\nu$, E_h is the hadron energy and ν is the virtual photon energy in the laboratory frame. The ratio $N_h(z_2|z_1 > 0.5)/N_h(z_1 > 0.5)$ is the per-event number of hadrons in events with at least one hadron with $z_1 > 0.5$. Absent from correlations introduced by nuclear effects, $R_{2h}(z_2)$ equals $R_h(z_2)$.

The HERMES collaboration presented R_{2h} measurements for DIS off nitrogen, krypton and xenon [51]. Their data showed evidence for correlated effects ($R_{2h} > R_h$), no significant A-dependence, and hints of enhancement at low-z_2 and a tendency for R_{2h} to approach unity as $z_2 \to 0.5$.

Majumder and Wang [52] described the data with a gluon bremsthralung model that incorporates correlations via the energy loss of the struck quark and the hadronization of the emitted gluons, although their model overpredicts the xenon data. Purely hadron absorption models predict no correlations and were strongly disfavoured by the HERMES data. However, Fialkowski and Wit [21] showed that selecting events with a high-z pion biases the hard scattering towards the nuclear surface, which introduces enough correlations to fit the data.

The HERMES di-hadron data lacks the precision to confirm the enhancement at low-z or the small A-dependence predicted by several models. It also lacks hadron identification, which was crucial to illuminate their single-hadron measurements [46, 47, 49].We propose to extend over the HERMES results by studying dihadron angular correlations with identified hadrons.

II. PRELIMINARY RESULTS USING 5 GEV DATA

Figure 2 show preliminary results[1] of R_{2h} for charged pions as a function of the fractional energy of the sub-leading pion, z_2, for carbon, iron and lead data. These values differ from the single-hadron multiplicity ratio, which show a more pronounced z-dependence ($1.0 \rightarrow 0.85$, $0.99 \rightarrow 0.68$, and $0.84 \rightarrow 0.53$ as as z ranges from $0.15 \rightarrow 0.5$ for carbon, iron and lead [53]). This result shows strong evidence for correlations introduced by nuclear effects.

Comparison with HERMES results show compatible enhancements at low z_2 but a stronger suppression at higher z_2. Unlike HERMES, our result shows evidence for a small but statistically significant A-dependence. The increase towards unity hinted by the HERMES result is not present in CLAS6 data. The average kinematics for our results is $\langle Q^2 \rangle = 1.6$ GeV^2 and $\langle \nu \rangle = 3.2$ GeV, whereas the HERMES result is at $\langle Q^2 \rangle = 2.4$ GeV^2 and $\langle \nu \rangle = 17.7$ GeV [51]. The significant differences between our data and HERMES results suggest a strong kinematic dependence of nuclear effects. The 11 GeV beam data would allow us to explore this in detail.

We compare our data with calculations made with the GiBUU Monte Carlo program [12] with the same kinematic selections as our data. GiBUU is a transport model based on the Boltzmann-Uehling-Uhlenbeck equation, which incorporates treatment of final-state interactions absorption and production mechanisms with elastic and inelastic channels. While GiBUU uses hadronic degrees of

[1] While these preliminary results do not include systematic uncertainties or acceptance corrections, most corrections and associated systematic uncertainties cancel in the ratio due for the dual-target configuration used during the EG2 run. These results are yet to be reviewed by the CLAS collaboration. An internal note is in preparation.

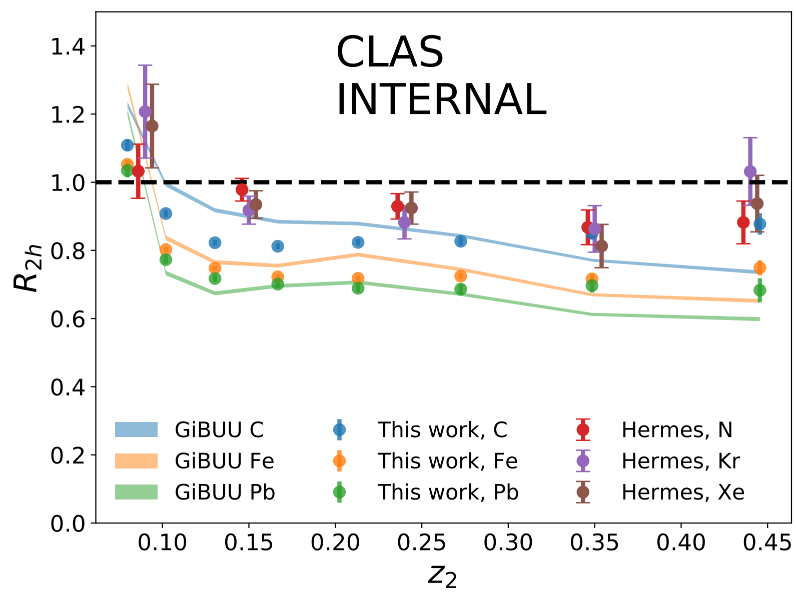

Figure 2. **CLAS6 Preliminary result**: Conditional suppression factor for charged pions as a function of sub-leading pion z. Points are slighted shifted horizontally for visibility. The open circles represent results by the HERMES experiment from Ref. [51]. The error bars in the CLAS data, which are most of the time smaller than the marker size, represent statistical uncertainties only. No acceptance or radiative-effect correction has been applied.

freedom, it incorporates formation times, "pre-hadron" interactions and color-transparency. These ingredients have been postulated to be necessary to describe nuclear modification of hadrons produced in DIS by the HERMES and EMC experiment [20].

While the GiBUU calculations reproduces some features of the data in a qualitatively way, the discrepancies have large statistical significance. Particularly, the predicted difference between iron and lead targets is not observed. In the GiBUU model, the low z_2 enhancement is produced by the interaction between hadrons produced in the primary electron-nucleon interaction with other nucleons as they propagate through nuclei. These are correlated with the intensity of the final-state interactions and probe the time-evolution of hadronization in nuclear DIS [25].

The results shown in Figure 2 integrate over the invariant mass of the pion pair. The HERMES analysis considered a variation that excluded the $\rho(770)$ mass region and found no difference [51],

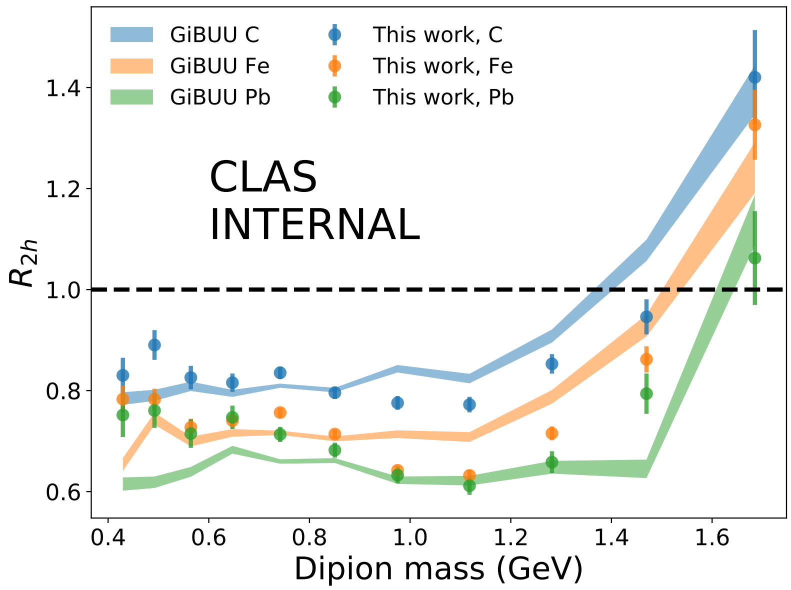

Figure 3. **CLAS6 Preliminary result**: Conditional suppression factor as a function of pion pair invariant mass. Points are slighted shifted horizontally for visibility. The error bars in the CLAS data represent statistical uncertainties only. No acceptance or radiative-effect correction has been applied.

but that comparison is limited by the relatively large statistical uncertainties of their data. Figure 3 shows the first measurement of R_{2h} as a function of the dipion invariant mass, for pairs with $z_2 > 0.15$ to focus on the suppression region.

The CLAS6 results show a weak dependence of the invariant mass of the pair on the region between 0.4–1.2 GeV, and a Cronin-like enhancement at higher invariant masses. This behaviour is qualitatively described by the GiBUU calculations. This result shows that the results from Figure 2 are not dominated by $\rho(770)$ production, which is consistent with the HERMES results.

Figure 4 shows R_{2h} as a function of the azimuthal [2] difference, $\Delta\phi_{pq}$, between the two pions. The data shows a strong dependence on $\Delta\phi_{pq}$ for all nuclei. This is qualitatively described by GiBUU model, which incorporates geometrical effects and path-length dependence. These results are qualitatively compatible with expectations from a "surface bias", i.e. the requirement of an

[2] The hadron azimuthal angle is defined between the leptonic plane, which is defined between the virtual photon and the outgoing lepton, and the hadronic plane, which is defined between the virtual photon and the hadron.

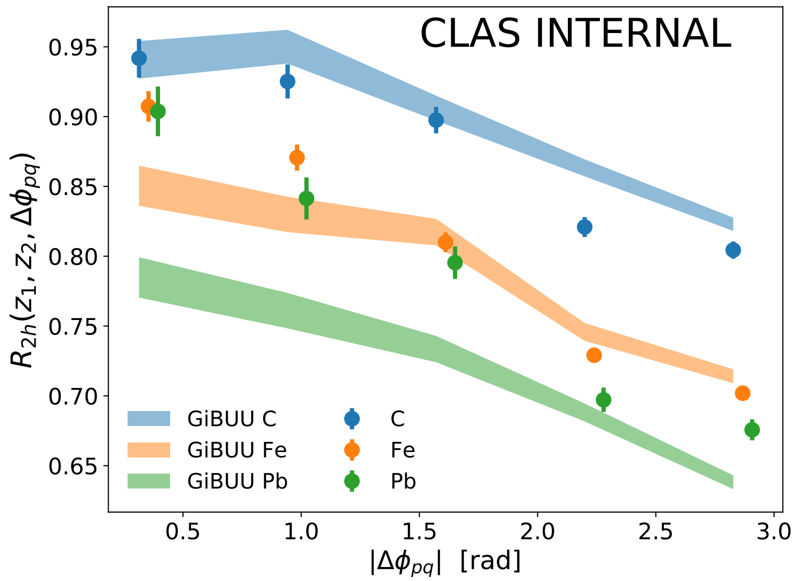

Figure 4. **CLAS6 Preliminary result**: Conditional suppression factor as a function of azimuthal difference of pion pair. Points are slighted shifted horizontally for visibility. The error bars in the CLAS data represent statistical uncertainties only. No acceptance or radiative-effect correction has been applied.

energetic hadron implies that hard scattering occurred near the surface of the nucleus and thus back-to-back pairs should be more strongly suppressed due to larger path-length. At our request, the GiBUU authors incorporated geometrical information in the output of their program (GiBUU 2019, patch number 7 related on June 3, 2020: `https://gibuu.hepforge.org/download`). We are in the process of using this information to guide the interpretation of our results.

Figure 5 shows a $R_{2h}(\Delta\phi_{pq})$ measurement as a function of sub-leading hadron momentum fraction. The figure also shows the correlation functions, which show a strength that grows with z_2. There are hints of a z_2 dependence of R_{2h} but the statistical uncertainty does not allow us to make conclusive statements. The GiBUU model does qualitatively describe the nuclear modification. The factor 10 higher luminosity expected to be collected by CLAS12 during the Run Group E will allow us to make a definite measurement. Without the full luminosity already granted to Run Group E, the investigation of this effect will be limited.

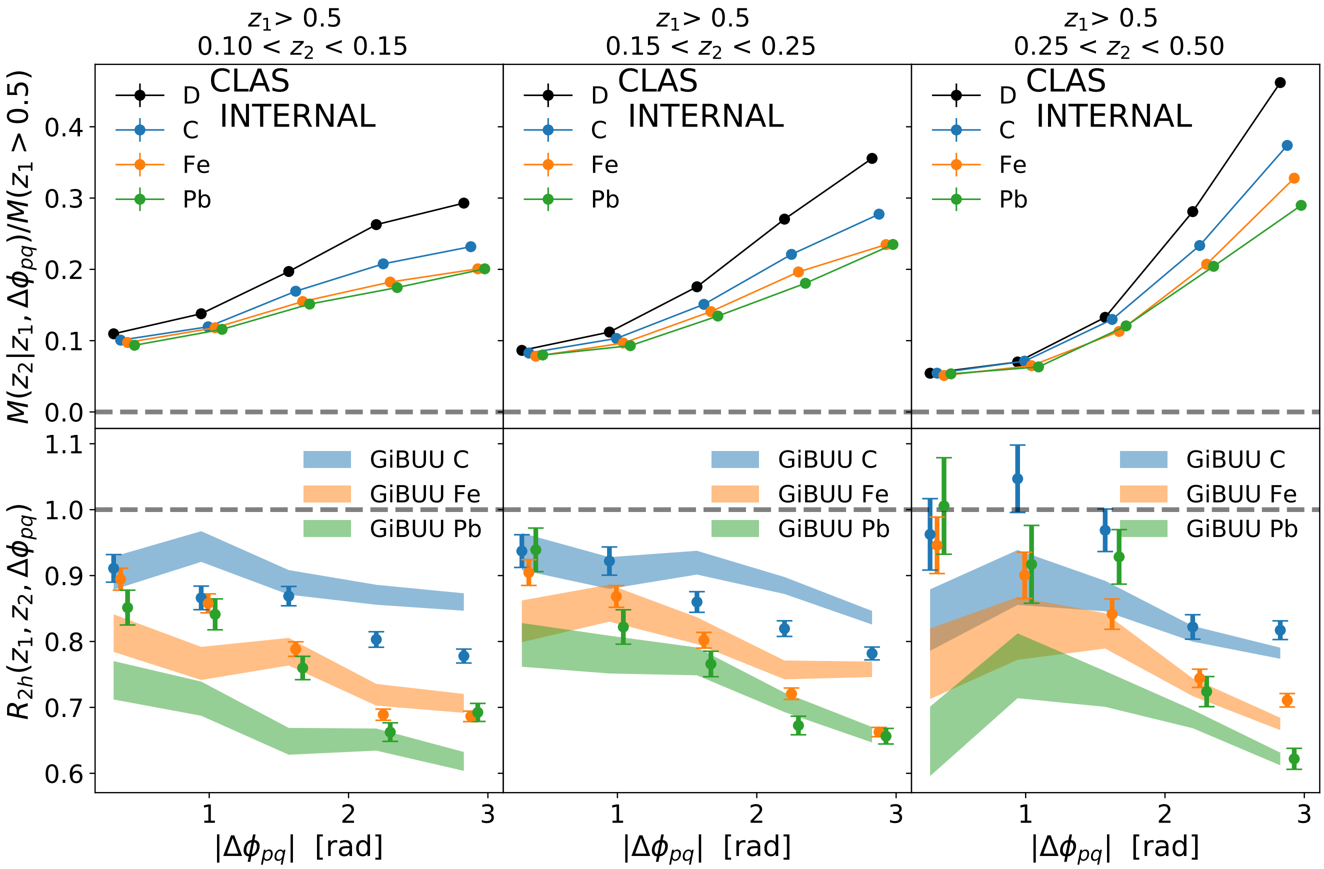

Figure 5. **CLAS6 Preliminary result**: Conditional suppression factor as a function of azimuthal difference of pion pair for various intervals of sub-leading hadron z. Points are slighted shifted horizontally for visibility. The error bars in the CLAS data represent statistical uncertainties only. No acceptance or radiative-effect correction has been applied.

III. PREDICTIONS FOR 11 GEV BEAM

In this section, we show projections for CLAS12 kinematics based on the GiBUU model. As shown in this the previous section, GiBUU does describe the CLAS6 data in a qualitatively way. Only predictions for lead target are shown. The event selection applied is $Q^2 > 1$ GeV^2, $W > 2$ GeV, $y < 0.85$, and at least one hadron with $z > 0.5$. The resulting kinematic coverage was illustrated in Figure 1.

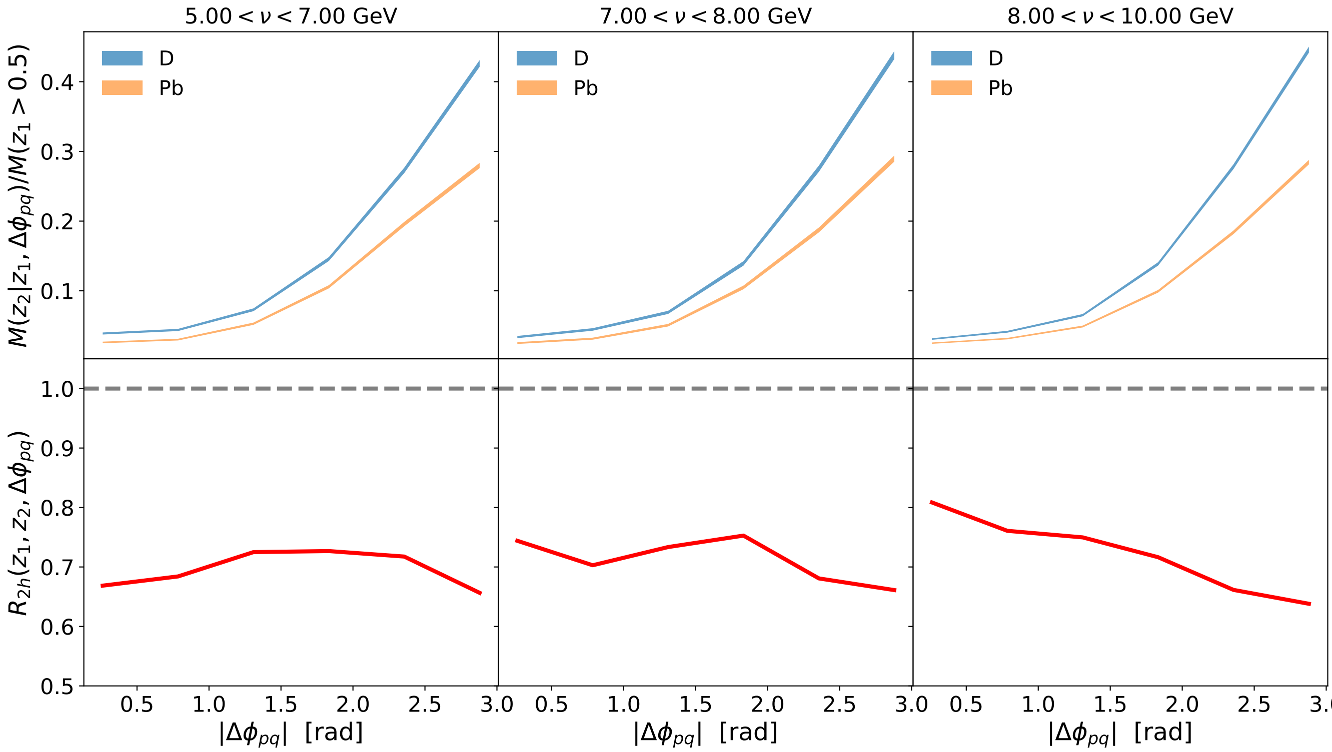

Figure 6. GiBUU prediction for conditional yield as a function of pair azimuthal separation for deuterium and lead targets with CLAS12 kinematics for various ν intervals.

The measurement on CLAS6 was performed at an average of $\langle\nu\rangle = 3.2$ GeV. The measurement with 11 GeV beam would allow us to extend the ν range up to 10 GeV, which overlaps with HERMES data. Figure 6 shows the predicted correlation function for deuterium and lead targets as well as the R_{2h} for various intervals of ν in the range $4 < \nu < 10$ GeV. The calculation is performed integrating over the sub-leading hadron over the range $z_2 > 0.1$. Figure 7 shows the GiBUU calculation but as a function of z_2 and integrated over ν. These are just illustrations of the multi-differential measurements that we plan to carry out with the CLAS12 data. An interesting prospect that we plan to explore is to measure 2D-angular correlations (azimuthal angle and rapidity).

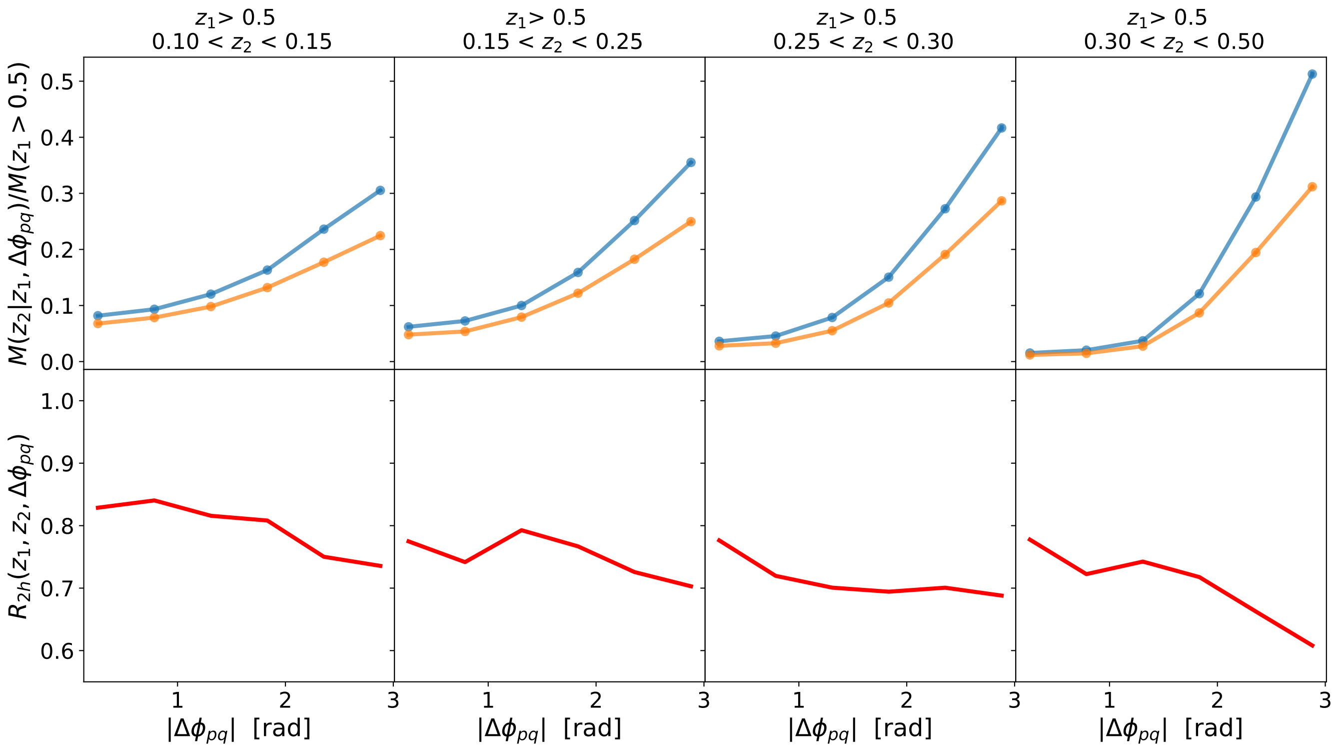

Figure 7. GiBUU prediction for conditional yield as a function of pair azimuthal separation for deuterium and lead targets with CLAS12 kinematics. Each panel shows the conditional yield (upper row) and lead-to-deuterium ratio (bottom panels) for various intervals of sub-leading pion momentum fraction, z_2.

IV. SUMMARY

We have proposed measurements of azimuthal correlations in dihadron production in deep-inelastic scattering off nuclei, which have never been measured before. This channel represents a new way to constrain correlated effects in hadron production in nuclei. We have shown that CLAS6 data shows promising results but that only the 11 GeV beam with the improved instrumentation of CLAS12 will allow us make definite measurements. The full beam time already granted to Run Group E is needed to elucidate the tantalizing kinematic effects seen in the CLAS6 data. These measurements will complement future EIC studies by covering a kinematic region that is difficult to measure in collider mode. The Run Group E represents the only prospect of new nuclear DIS data with a high-acceptance detector before the EIC, so it provides a path-finder opportunity for hadronization studies. Ultimately, these studies will allow us to explore in a new way cold-nuclear matter effects and explore the interplay between hadronic and partonic degrees of freedom.

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