Di-hadron Correlations in Electro-nuclear Scattering

Dr. Sebouh Paul
UC Riverside
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UC RIVERSIDE

CEBAF Large Acceptance Spectrometer

Previous measurements highlighted in LRP

- Referencing our published di-pion ratio measurement*,
  - “Highlights since the 2015 Long-Range Plan include … an investigation by the CLAS experiment of how hadron-pair production is modified in cold nuclear matter …”
- “More questions” posed by LRP
  - What are the timescales of color neutralization and hadron formation
  - “How are the various hadrons produced in a scattering process correlated with one another and how does hadronization change in a dense partonic environment?”
- Our new dipion and pion-proton correlation measurements can helps to answer these questions

Sidebar 3.3 Connecting the World of QCD to the Visible World

Because of confinement, we never observe the color-charged particles of QCD—quarks and gluons—in isolation; they are confined to color-neutral hadrons. Thus, every time a high-energy collision breaks up a proton, the energy of the collision allows the creation of more quark–antiquark pairs by converting energy into mass (E = mc2), and the new quarks and antiquarks rapidly bind to the various constituents of the broken-up proton, “snapping” into mesons and baryons, the QCD bound states, which can be detected.

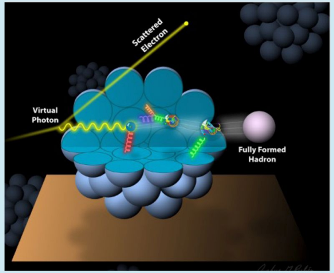


Figure 1. Representation of a high energy collision [S12]

Like blowing soap bubbles from the film with a bubble wand, when every free-streaming bubble must have closed off to become a whole bubble, every free-streaming product of a high-energy collision must have somehow become a “whole” color-neutral particle (Fig 1). Each time you blow on the soap film, a different number of bubbles of varying sizes may be produced. Likewise, each time a high-energy collision involving a proton occurs, a different number of hadrons of varying masses and quantum numbers may be produced.

To date, most efforts have focused on studying the production of a single hadron at a time along the same direction as the outgoing parton. However, in recent years, we have started to study hadronization in more sophisticated ways. Highlights since the 2015 Long Range Plan include spin–momentum correlation measurements in hadronization by the STAR experiment at RHIC, multivariable measurements of identified hadron production in jets by the LHCb experiment at CERN, an investigation by the CLAS experiment at Jefferson Lab of how hadron-pair production is modified in cold nuclear matter, and the modifications to hadrons in jets induced by interactions with the quark–gluon plasma, observed at both RHIC and the LHC.

These exciting results naturally point to more questions.

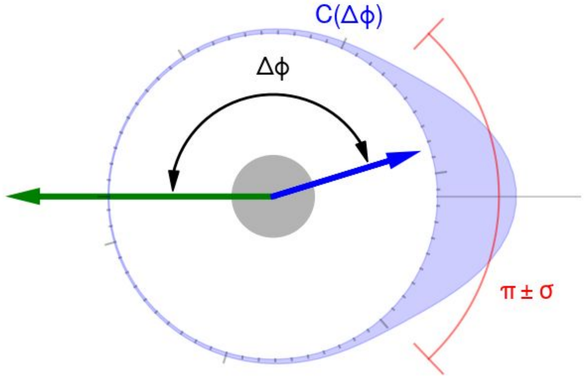
- What are the timescales of color neutralization and hadron formation?
- What are the differences in hadronization of quarks versus gluons and of light quarks versus heavy quarks?
- How are the various hadrons produced in a single scattering process correlated with one another, and how does hadronization change in a dense partonic environment?

The upcoming decade holds great promise for advancements, both in how we think about hadronization theoretically and in our ability to experimentally untangle the various mechanisms that contribute to this phenomenon. Theoretically, recent developments in quantum computing provide unique opportunities to explore the inherent dynamic nature of hadronization as a process unfolding in time. Experimentally, hadron identification capabilities at the STAR experiment at RHIC, CLAS12 experiment at Jefferson Lab, LHCb and ALICE experiments at CERN, Belle II experiment in Japan, and the ePIC experiment at the future EIC will allow us to measure and compare a wide range of traditional and novel observables related to hadronization.

*S.J Paul et al (CLAS Collab.) Phys. Rev. Lett. 129, 182501 (2022)

Outline

- Dipion correlations in CLAS6 (in ad-hoc review)
- Pion-proton correlations in CLAS6 (new analysis)
- Planned correlation measurements in CLAS12 EG2



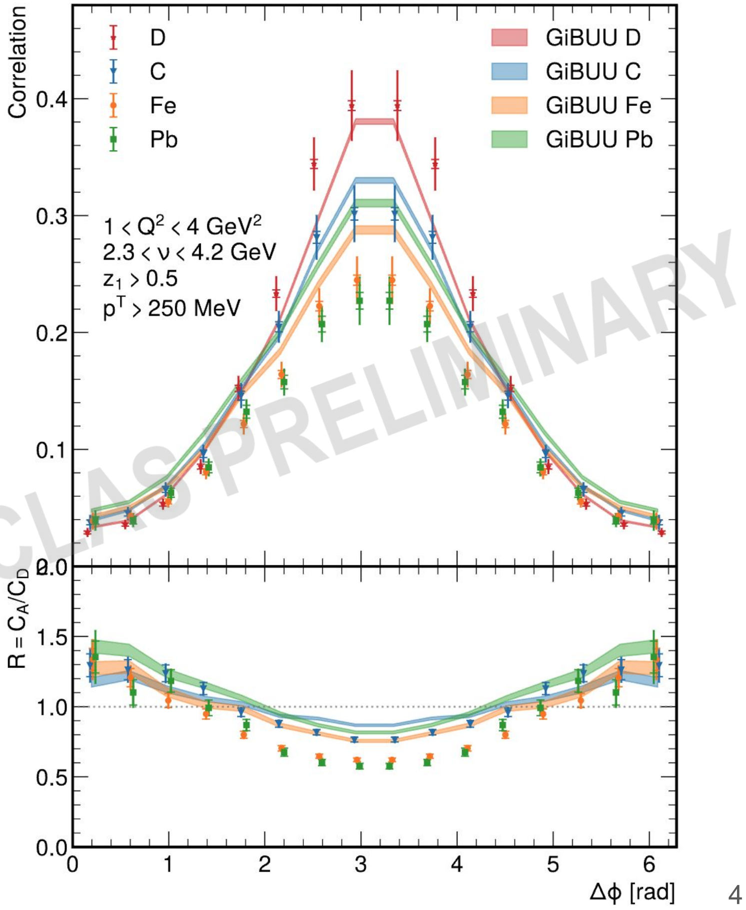
How are the various hadrons produced in a scattering process correlated with one another ?

Our observable: correlation function

$$C(\Delta\phi) = C_0 \frac{1}{N_{eh}} \frac{dN_{ehh}}{d\Delta\phi}$$

- Δφ is the difference in azimuth
- N_{eh} is the number of events with scattered electron and a "leading hadron" ($z=E_h/\nu>0.5$)
- N_{ehh} is the number of "subleading hadrons" in those events
- C_0 is the normalization factor (use same value for all targets)

Leading π⁺, subleading π⁻

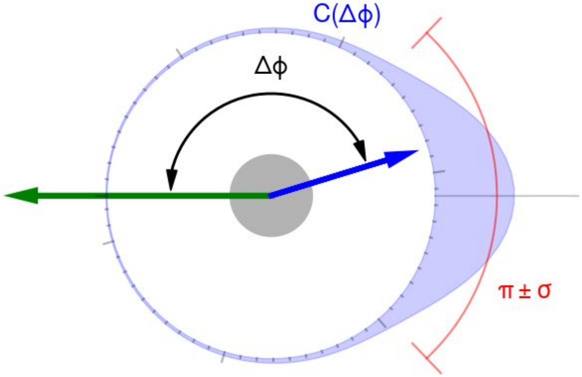


Derived quantities: RMS widths and broadenings

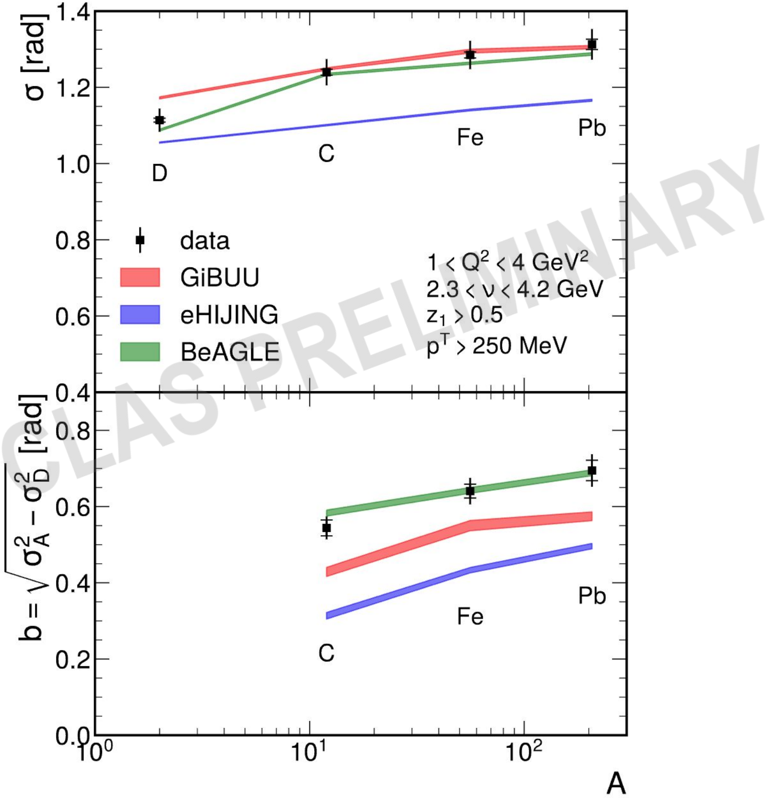
RMS width:

$$\sigma = \sqrt{\frac{\int_0^{2\pi} d\Delta\phi\, C(\Delta\phi)(\Delta\phi - \pi)^2}{\int_0^{2\pi} d\Delta\phi\, C(\Delta\phi)}}$$

Broadening: $b = \sqrt{\sigma_A^2 - \sigma_D^2}$



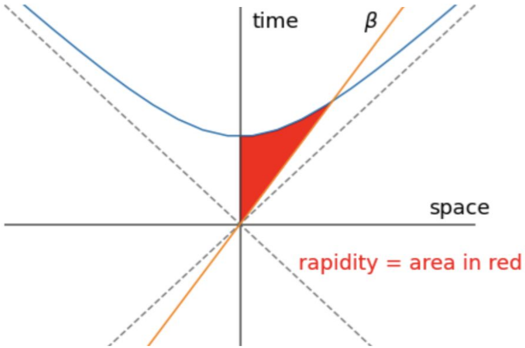
Leading π⁺, subleading π⁻

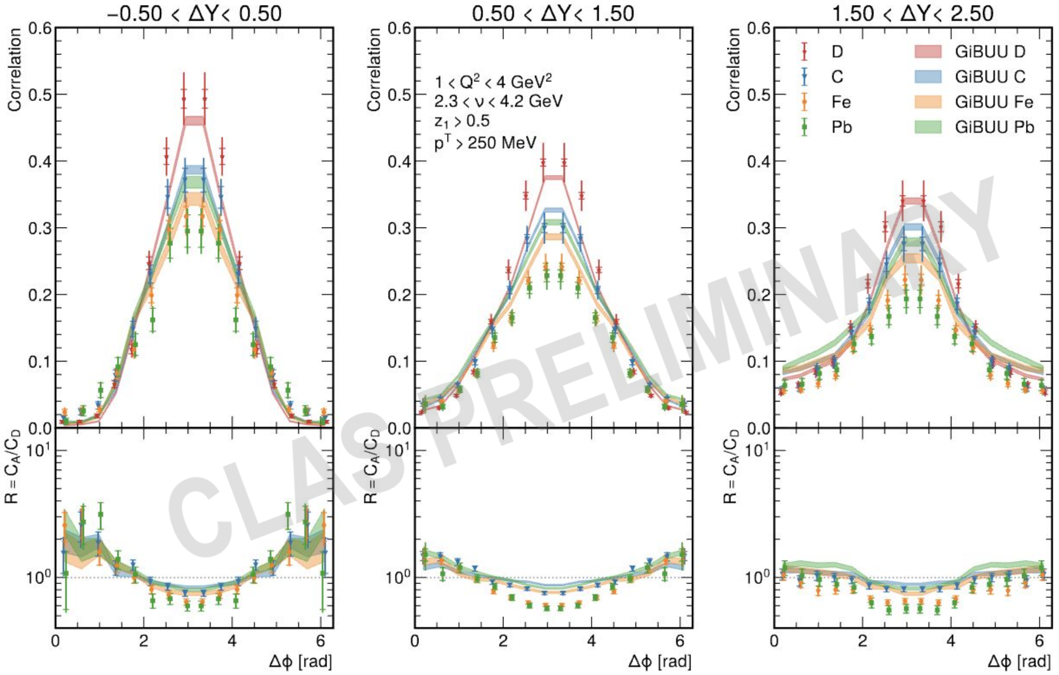


Multidimensional measurements

- Correlation functions can be measured in bins of multiple variables, such as
  - rapidity difference, $\Delta Y = Y_1 - Y_2$
  - transverse momentum of the leading hadron, p_T^1
  - subleading hadron p_T^2

$$Y = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$

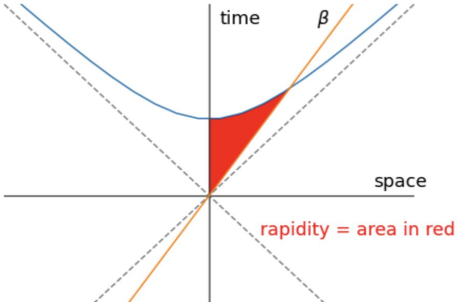


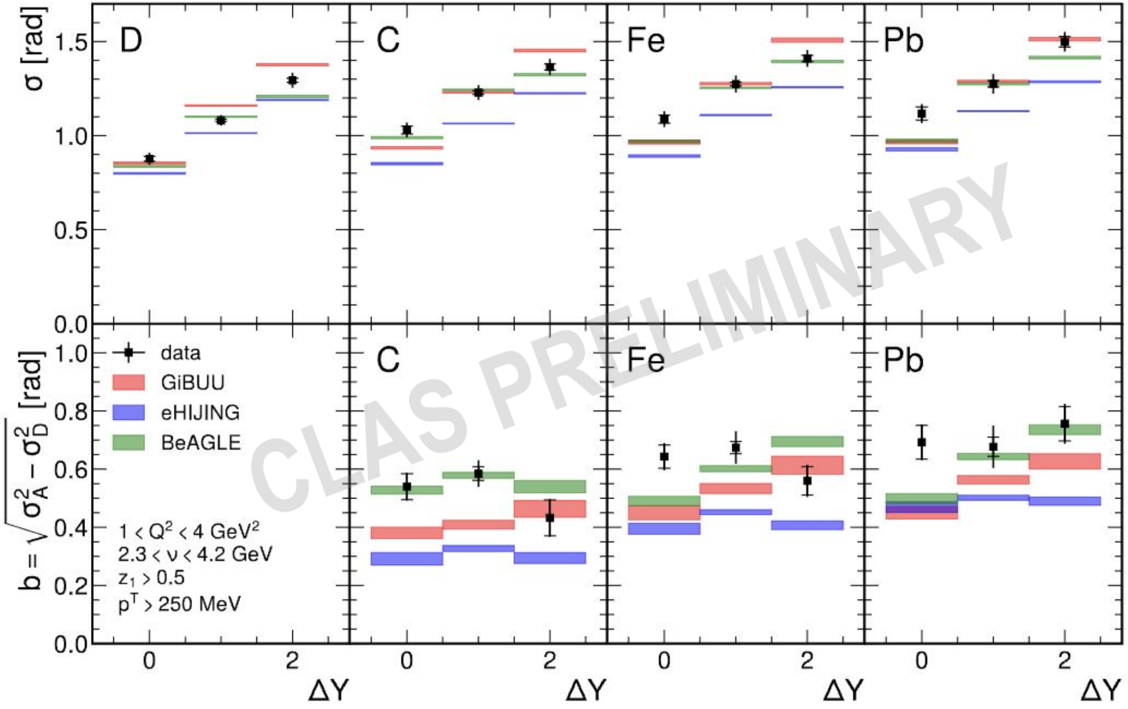


Multidimensional measurements

- Widths and broadenings can also be evaluated in these bins

$$Y = \frac{1}{2}\ln\frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$





Di-pion correlations analysis (in ad-hoc review)

- Follows up our published di-pion ratios measurement→ PRC
- Round 1 started Jan 23, ended Feb. 22
- Sent response to reviewers this weekend (3/9)
  - Clarified some things that were less clear
  - Updated the format to some of the plots

Dihadron Azimuthal Correlations in Deep-Inelastic Scattering Off Nuclear Targets

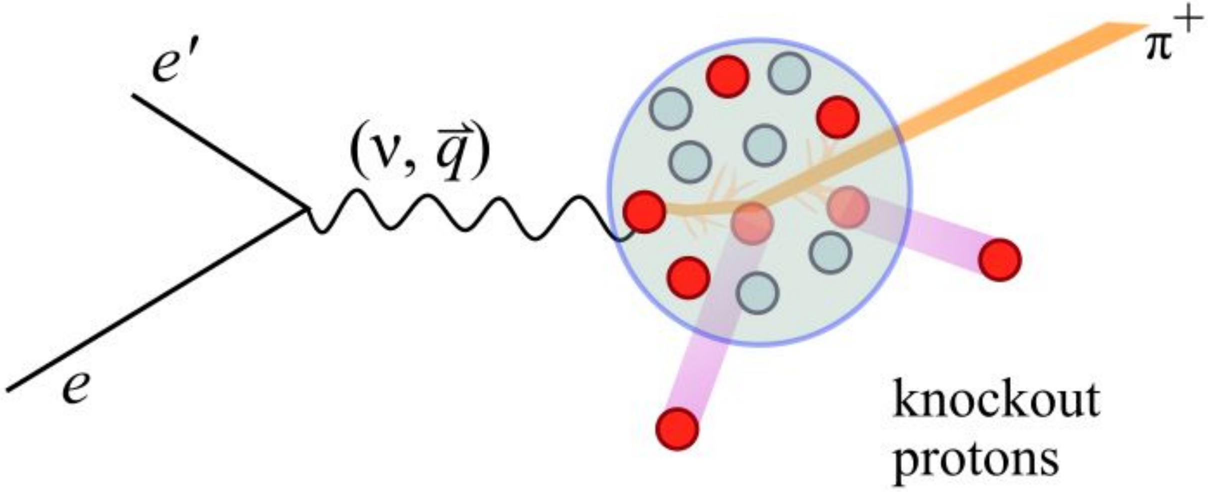
Sebouh J. Paul, Sebastián Morán, Miguel Arratia, William Brooks,
Hayk Hakobyan, Ahmed El Alaoui, and others (CLAS Collaboration)*

(Dated: March 10, 2024)

We measured the nuclear dependence of the di-pion azimuthal correlation function in deep-inelastic scattering (DIS) using the CLAS detector and CEBAF's 5 GeV electron beam. As the nuclear-target size increases, transitioning from deuterium to carbon, iron, and lead, the correlation function broadens monotonically. Its shape exhibits a significant dependence on kinematics, including the transverse momentum of the pions and the difference in their rapidity. None of the various Monte-Carlo Event generators we evaluated could fully replicate the observed correlation functions and nuclear effects throughout the entire phasespace. As the first study of its kind in DIS experiments, this research provides an important baseline for enhancing our understanding of the interplay between the nuclear medium and the hadronization process.

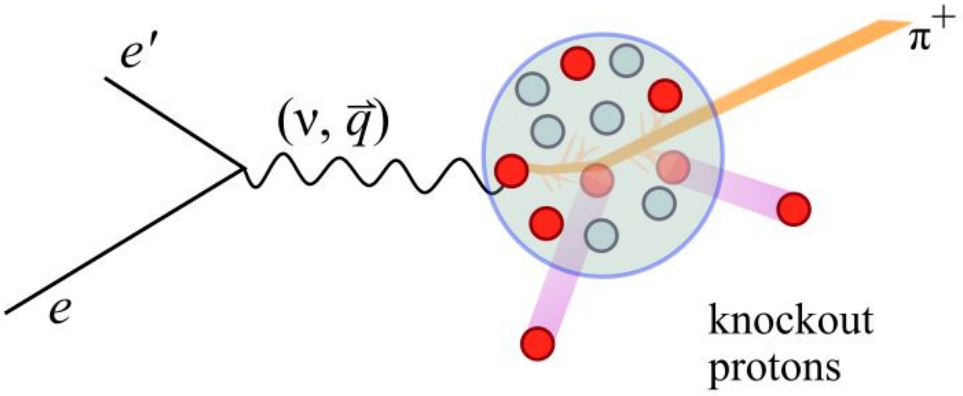
New analysis!   Proton knockout with leading pion

- In a nuclear DIS reaction, either the leading hadron (from the struck quark) or a cascade can knock protons out
- In this reaction, we measure the azimuthal and longitudinal correlations between the measured leading hadron and a knocked-out proton



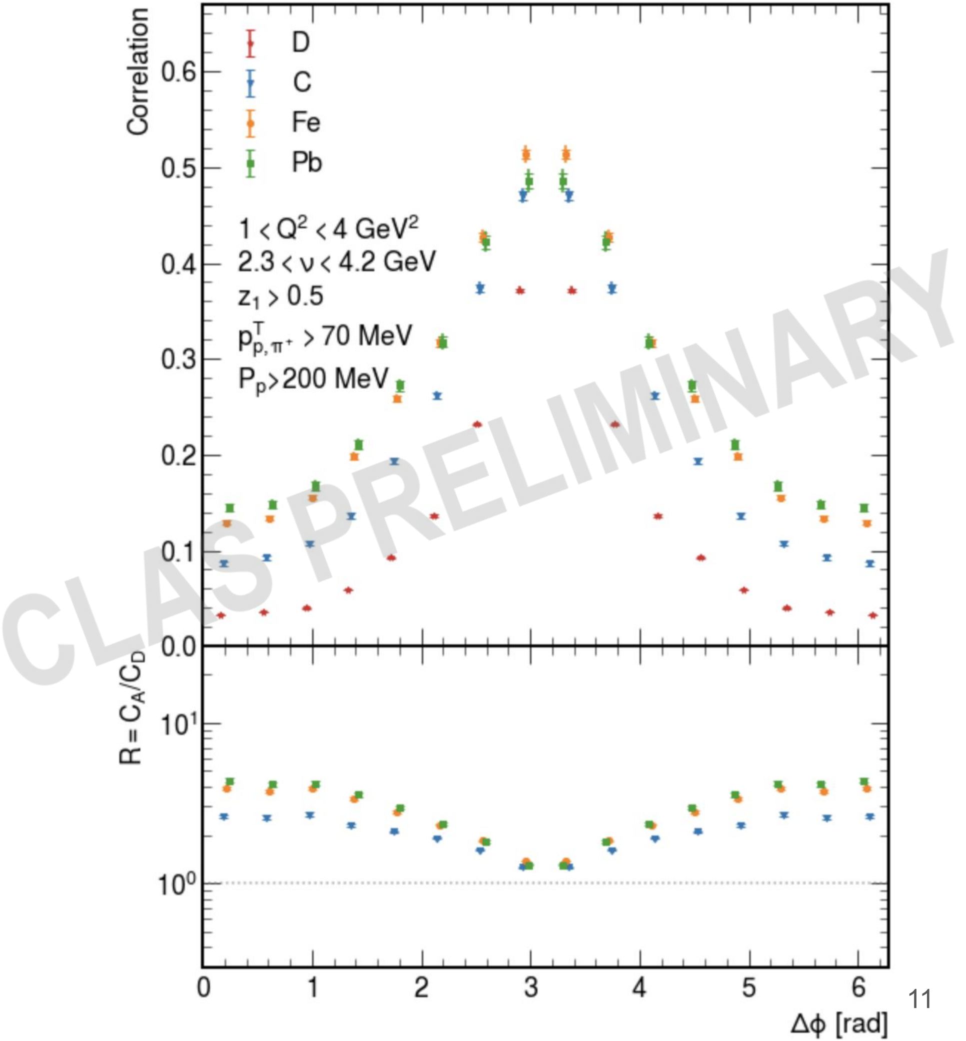
Event selection

- Electron with DIS kinematics
  - $Q^2>1$ GeV^2
  - W>2 GeV
  - 2.3<ν<4.2 GeV
- Leading π+
  - $z=E_h/\nu>0.5$
  - Identified with
    - TOF only (P<2.7 GeV)
    - TOF+CC (P>2.7 GeV)
- Proton
  - TOF cuts following O. Hen et al.
  - 0.2<P<2.8 GeV
- Both hadrons:
  - pT>70 MeV



Results for the pion-proton analysis

- Similar to di-pion analysis…,
  - Peak is at Δφ=π,
  - Wider correlation functions for nuclear than for deuterium
- But unlike di-pion case…
  - Taller peaks for nuclear than for deuterium,

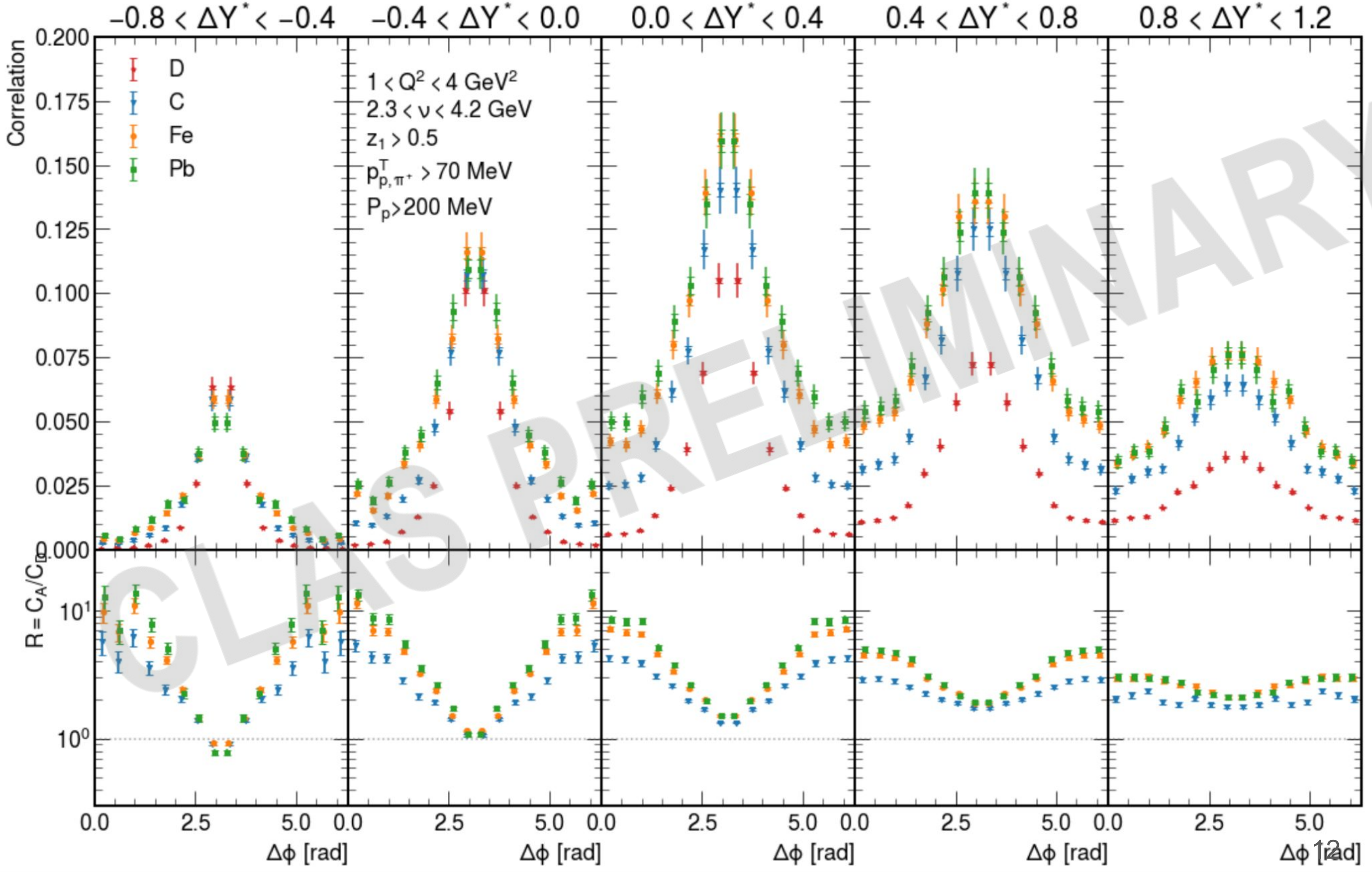


Multidimensional πp results:

$$\Delta Y^* = Y_{\pi^+} - Y_p - (Y_{\text{cm}} - Y_{\text{lab}})$$

$$Y = \frac{1}{2}\ln\frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$

- Peak heights largest at low |ΔY*|
- Wider correlation functions for larger positive ΔY*
- Nuclear data
  - Larger peak heights than deuterium for most ΔY* bins, especially at large positive ΔY*



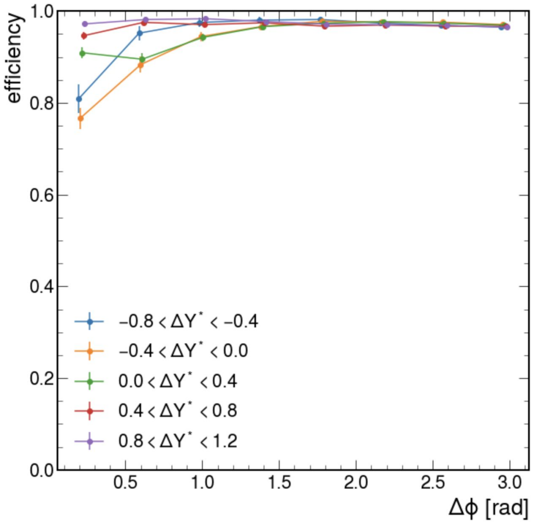
Efficiency studies

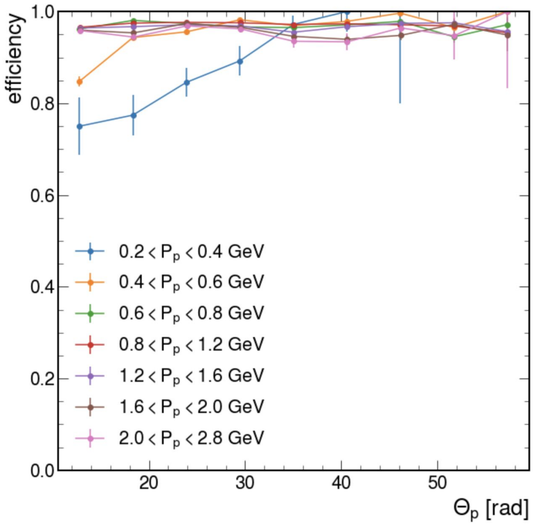
MC method

- eff=recon(e'πp)/(gen(p)&recon(e'π))
- Seem to indicate very high detection efficiency except at very specific kinematics

Mixed event method (TO DO)

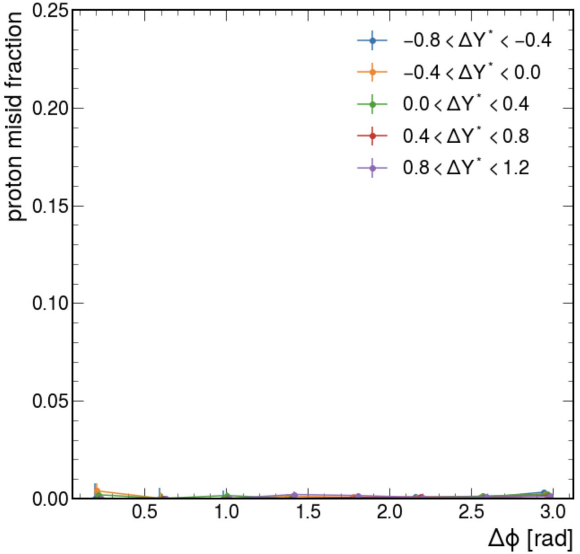
- Combine pion from one event and proton with another to create "mixed sample"
- Deviations in Δφ, ΔY distribution from flatness indicates variation in pair acceptance

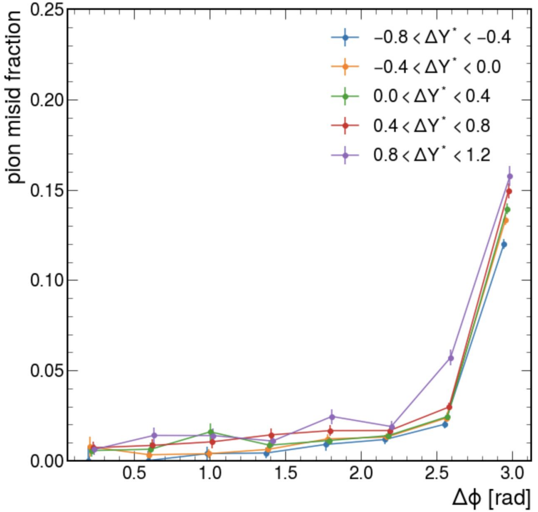




Particle Misidentification in MC

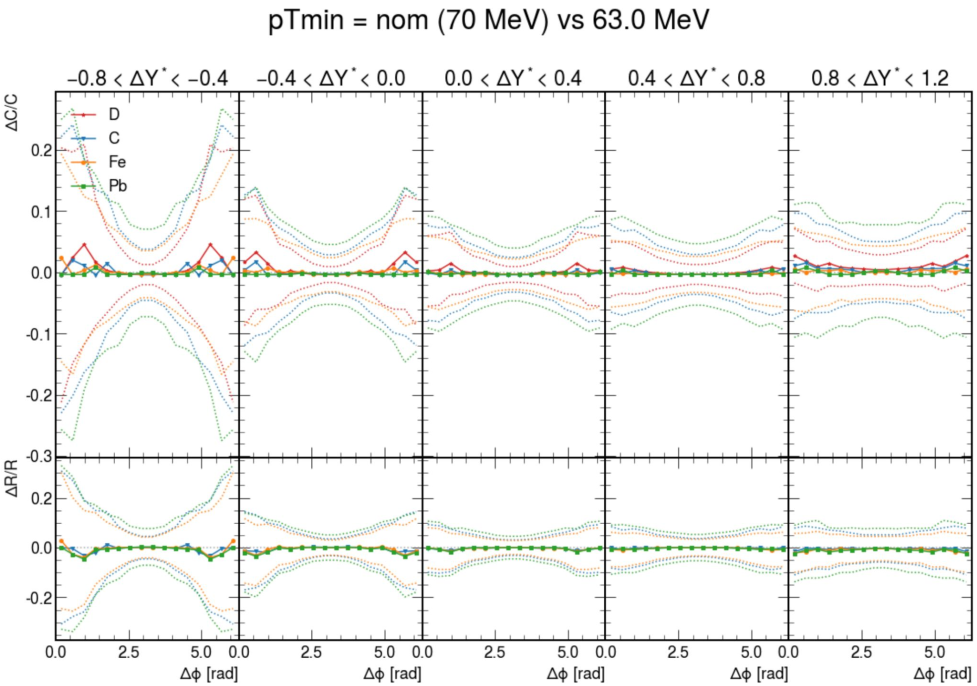
- Misid fraction: f_{misid} = fraction of events where truth pid does not match recon pid
- Sub-leading proton misidentification is negligible (<1%)
- Leading pion misidentification is higher (due to larger momentum)
  - 1-2% for most bins
  - Up to 7% for 7th |Δφ| bin
  - Up to 16% for 8th |Δφ| bin
- Systematic uncertainty is $\Delta C/C = f_{misid}$



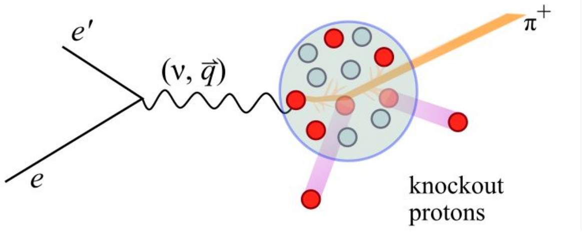


Systematics from event-selection cuts

- Repeated analysis with varied event selection cuts and compared with nominal
  - TOF cuts (10% tighter or 10% looser than nominal, vs nominal)
  - Minimum proton momentum (220 MeV vs nominal 200 MeV)
  - Minimum transverse momentum (63 MeV or 77 MeV vs nominal 70 MeV)
- Deviations from nominal are much smaller (less than half) than the statistical uncertainties for most bins



Further plans with the pion-proton analysis



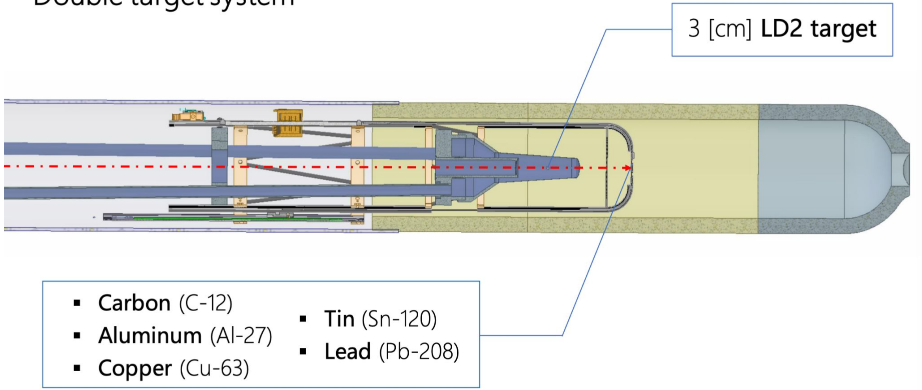
- Correction for pair-acceptance effects
  - Event-mixing study, similar to di-pion analysis
- Continue writing the analysis note
  - Write introduction
  - Continue documentation of the sources of systematic uncertainties
- Compare data to event-generators
  - Plan to compare results to calculations from GiBUU, eHIJING, and BeAGLE models
  - Working with GiBUU and eHIJING authors to get HepMC3 output so that we can have a uniform framework (Rivet) for extracting values from generated events
    - Less work in the long run.
    - Can count as service work
- Submit for analysis review, followed by ad-hoc and collaboration-wide reviews
  - Target journal is PRL

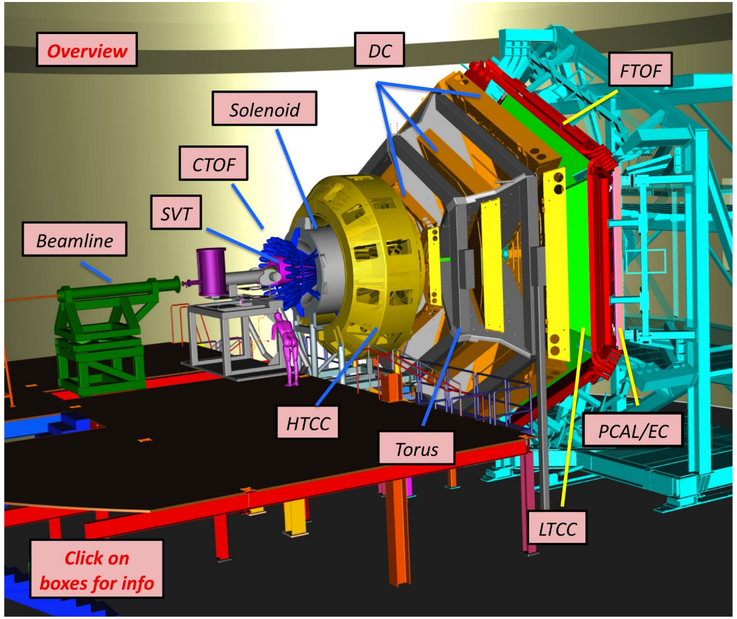
Follow-up measurements with CLAS12 RGE

These di-hadron measurements can be extended in the upcoming Run-Group E with

- Higher luminosity
- Higher beam energy
- Polarized electron beam
- Larger variety of targets

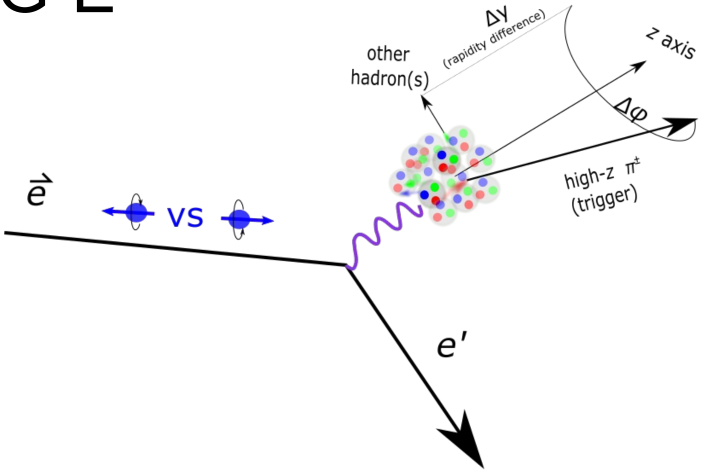
Double target system

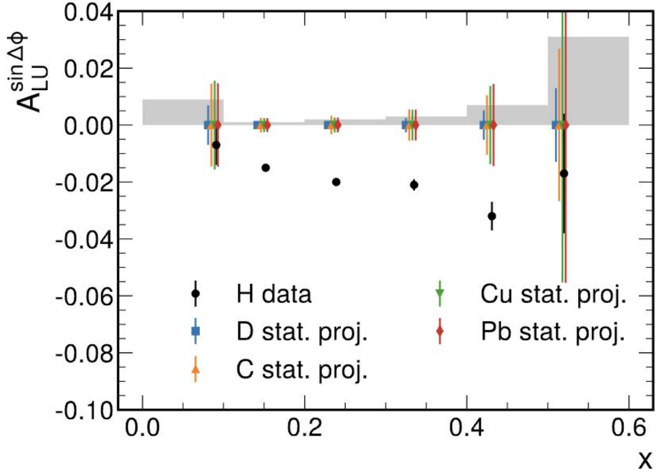


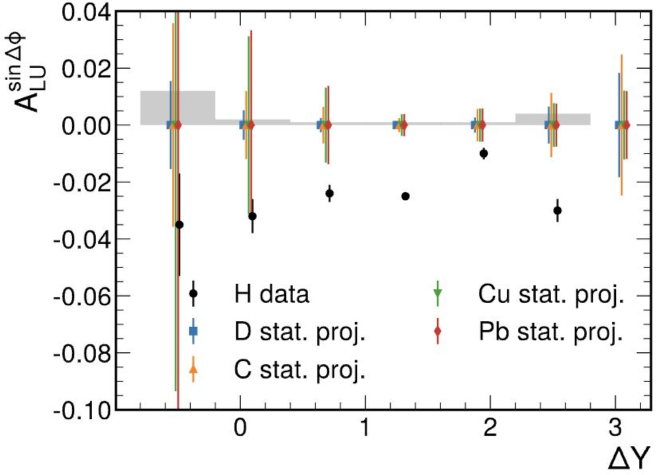


Dihadron beam-spin asymmetry in RG-E

Beam polarization in RG-E will allow us to compare beam-spin asymmetries in nuclei versus deuterium, and also compare to existing hydrogen CLAS12 data.







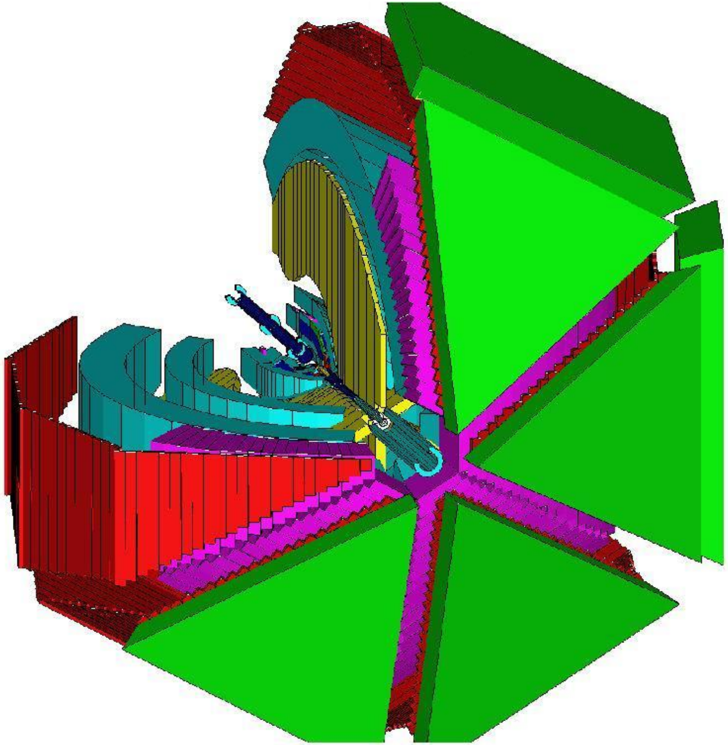
Summary

- Di-hadron correlations offer unique insights into how hadronization is affected by the presence of nuclear material
- Di-pion correlations paper has just completed first round of ad-hoc review
  - Target journal: PRC
- Pion vs. knockout-proton correlations analysis is undergoing
  - Analysis note expected to be ready for review within the next few months
  - Target journal is PRL
- Upcoming RGE measurements will extend these measurements with even higher precision, and will introduce a polarization as a new probe.

Backup slides

Dataset/Experimental Setup (EG2)

- CLAS detector at JLab
- 5 GeV e^- beam
- Liquid deuterium target in tandem with nuclear targets*: C, Fe, and Pb
- Reduces systematic errors for A vs. D comparisons



*NIM A 592 (2008) 218– 223

Notes on multidimensional pion-proton analysis

$$C(\Delta\phi, \Delta Y) = C_0 \frac{1}{N_{e'\pi^+}} \frac{d^2 N_{e'\pi^+ p}}{d\Delta\phi \; d\Delta Y^*}$$

- $\Delta\varphi$ is the difference in azimuth
- $\Delta Y^* = Y_1 - Y_2 - (Y_{cm} - Y_{lab})$ $\quad Y = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$
    - Distribution is centered near zero, unlike ΔY
    -
- C_0 defined such that integral over $\Delta\varphi$ and $d\Delta Y^*$ for deuterium; use same constant for all targets