Status update of the di-pion production in eA scattering

CEBAF Large Acceptance Spectrometer

Sebouh Paul
CLAS Collab Meeting
11/8/23

Status of Analysis Review

- Completed 10/31/2023
- Preparing draft of paper for ad-hoc review

Multi-dimensional analysis of correlations in di-pion electro-production off nuclei with EG2 data

-

CLAS ANALYSIS NOTE
VERSION 2

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A multi-dimensional measurement of azimuthal correlations in deep inelastic scattering off nuclei with the CLAS spectrometer

Sebouh J. Paul, Miguel Arratia, Sebastián Morán, William Brooks, Hayk Hakobyan and CLAS*
(Dated: November 5, 2023)

We present a measurement of the nuclear dependence of di-hadron production in deep-inelastic scattering off nuclei using the CLAS detector and the CEBAF 5.014 GeV electron beam. Our measurements show a clear peak for azimuthally back-to-back ($\Delta\phi \approx \pi$) pairs of charged pions for nuclear and deuterium targets. We find that this peak is wider and shorter for the heavier nuclear targets, indicating that there are both smearing and suppression effects in nuclei. Further, we observe a strong dependence of the shapes of these functions on the event kinematics. The peaks are wider with larger rapidity separation, and narrower if either of the two particles has a large transverse momentum. Our results complement earlier studies which focused on the nuclear-to-deuterium ratios of the di-hadron production rates.

I. INTRODUCTION

Studies of electron deep inelastic scattering (DIS) off nuclei can elucidate emergent dynamics of the strong interactions, such as quark transport in matter and hadronization [1]. Moreover, nuclear effects in hadron production also illuminate neutrino-oscillation experiments [2] such as the future DUNE [3], for which multi-pion production in DIS off argon dominates the total cross-section [4]

also measured its dependence on the di-pion invariant mass, $m_{\pi\pi}$, and the azimuthal angular difference $\Delta\phi$ between the two pions (relative to the virtual-photon direction). In this work, we expand upon the di-pion results of Ref. [31] by also introducing, in addition to $\Delta\phi$, three additional binning variables, each of which are invariant under boosts along the virtual photon direction. The first is the rapidity difference of the two hadrons, $\Delta Y = Y_1 - Y_2$, where the rapidities are given by

Highlighted in LRP

- Referencing our previous di-hadron publication*
  - “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 will be addressed by our planned analyses with 11 GeV data

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.

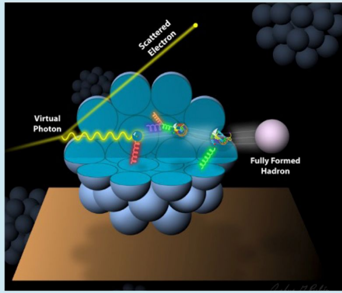


Figure 1. Representation of a high energy collision [S12]

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 dire tion as the outgoing parton. However, in recent years, we have started to study hadronization in more sophisticat ways. Highlights since the 2015 Long Range Plan include spin–momentum correlation measurements in hadro nation by the STAR experiment at RHIC, multivariable measurements of identified hadron production in jets by t LHCb experiment at CERN, an investigation by the CLAS experiment at Jefferson Lab of how hadron-pair producti 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.

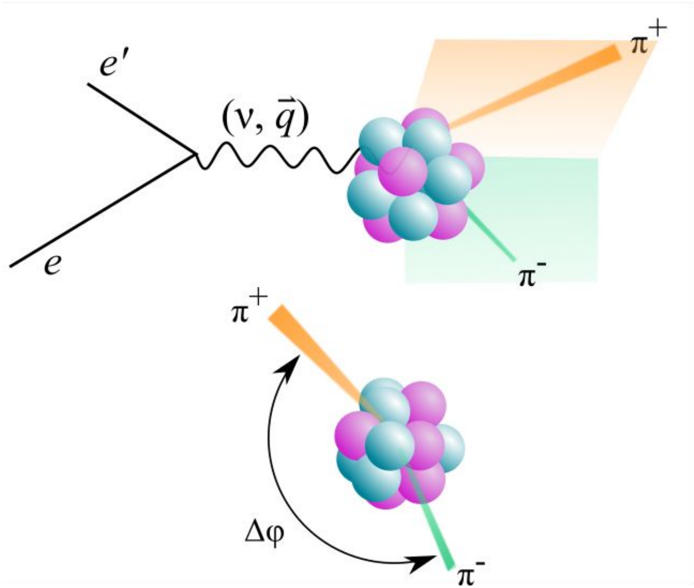
- What are the timescales of color neutralization and hadron formation?
- What are the differences in hadronization of quarks versus gluons and of light quarks versus heavy quarks?
- How are the various hadrons produced in a single scattering process correlated with one another, and how does hadronization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

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

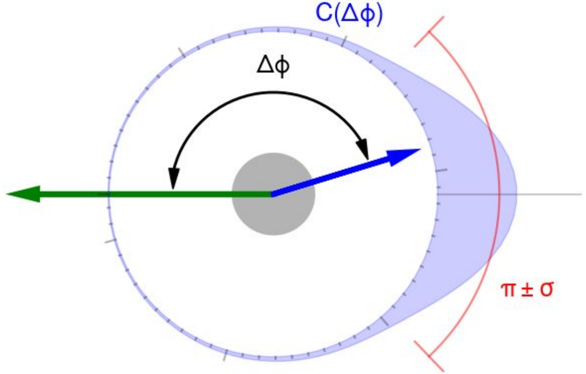
https://nuclearsciencefuture.org/wp-content/uploads/2023/10/NSAC-LRP-2023-v1.2.pdf p. 25

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

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



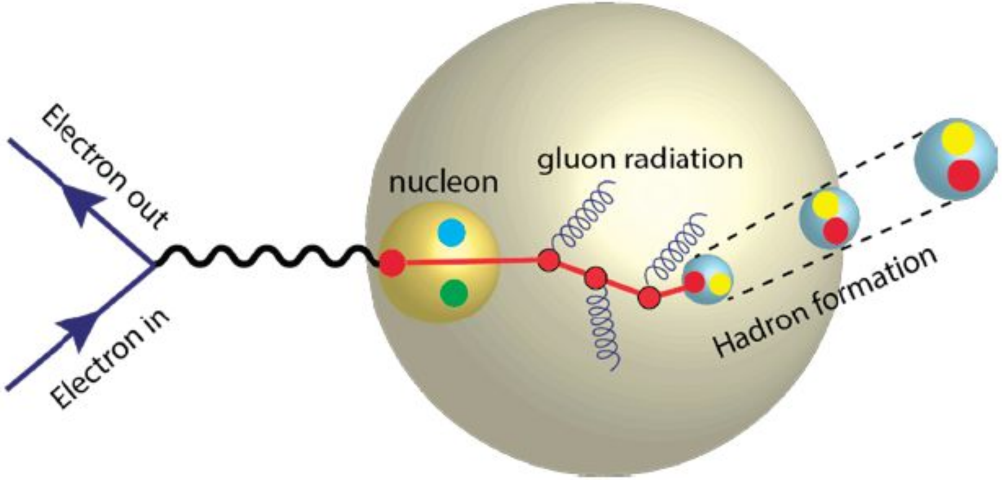
$$C(\Delta\phi) = C_0 \frac{dN_{2h}}{d\Delta\phi} \frac{1}{N_h}$$



* C_0 chosen such that $\int_0^{2\pi} d\,\Delta\phi\; C(\Delta\phi) = 1$ for deuterium

… and how does hadronization change in a dense partonic environment?

And what are the timescales of color neutralization and hadron formation?



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What is new since last collaboration meeting

- Updated central value of correlation functions by updating the acceptance correction.
- Updated layout of plots for paper.
- Added two new Monte-Carlo Generators, which appeared in the arXiv within the past two years:
  - eHIJING
  - BeAGLE
- These models mainly developed for EIC, but also work and were compared to fixed target data, including our CLAS single-charged pion paper (Moran et al.)

arXiv > hep-ph > arXiv:2304.10779

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High Energy Physics - Phenomenology

[Submitted on 21 Apr 2023]

eHIJING: an Event Generator for Jet Tomography in Electron-Ion Collisions

Weiyao Ke, Yuan-Yuan Zhang, Hongxi Xing, Xin-Nian Wang

We develop the first event generator, the electron-Heavy-Ion-Jet-Interaction-Generator (eHIJING), for the jet tomography study of electron-ion collisions. In this generator, energetic jet partons produced from the initial hard scattering undergo multiple collisions with the nuclear remnants with a collision rate that is proportional to the transverse-momentum-dependent (TMD) gluon densities in the nucleus. Medium-modified QCD parton splittings within the higher-twist and generalized higher-twist framework are utilized to simulate parton showering in the nuclear medium that takes into account the non-Abelian Landau-Pomeranchuck-Midgal interference in gluon radiation induced by multiple scatterings. The TMD gluon distribution inside the nucleus is given by a simple model inspired by the physics of gluon saturation. Employing eHIJING, we revisit hadron production in semi-inclusive deep inelastic scattering (SIDIS) as measured by EMC, HERMES as well as recent CLAS experiments. eHIJING with both the higher-twist and generalized higher-twist framework gives reasonably good descriptions of these experimental data. Predictions for experiments at the future electron-ion colliders are also provided. It is demonstrated that future measurements of the transverse momentum broadening of single hadron spectra can be used to map out the two dimensional kinematic (Q^2, x_B) dependence the jet transport parameter $\hat{q}$ in cold nuclear matter.

arXiv > physics > arXiv:2204.11998

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Physics > Computational Physics

[Submitted on 13 Apr 2022]

BeAGLE: Benchmark eA Generator for LEptoproduction in high energy lepton-nucleus collisions

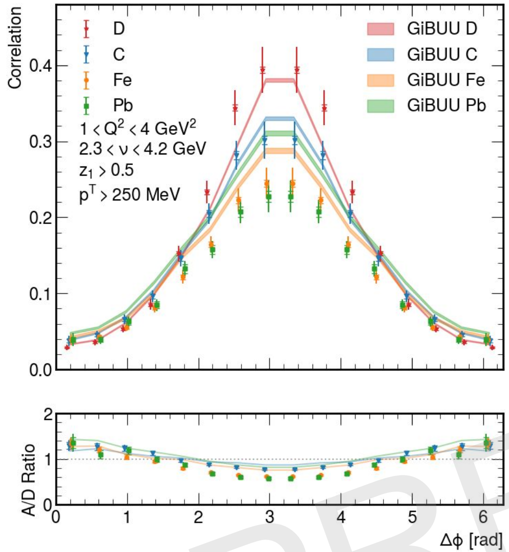
Wan Chang, Elke-Caroline Aschenauer, Mark D. Baker, Alexander Jentsch, Jeong-Hun Lee, Zhoudunming Tu, Zhongbao Yin, Liang Zheng

The upcoming Electron-Ion Collider (EIC) will address several outstanding puzzles in modern nuclear physics. Topics such as the partonic structure of nucleons and nuclei, the origin of their mass and spin, among others, can be understood via the study of high energy electron-proton (ep) and electron-nucleus (eA) collisions. Achieving the scientific goals of the EIC will require a novel electron-hadron collider and detectors capable to perform high-precision measurements, but also dedicated tools to model and interpret the data. To aid in the latter, we present a general-purpose eA Monte Carlo (MC) generator - BeAGLE. In this paper, we provide a general description of the models integrated into BeAGLE, applications of BeAGLE in eA physics, implications for detector requirements at the EIC, and the tuning of the parameters in BeAGLE based on available experimental data. Specifically, we focus on a selection of model and data comparisons in particle production in both ep and eA collisions, where baseline particle distributions provide essential information to characterize the event. In addition, we investigate the collision geometry determination in eA collisions, which could be used as an experimental tool for varying the nuclear density.

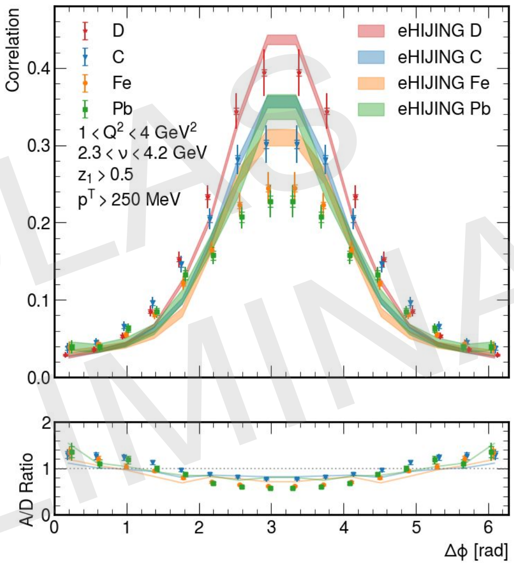
Comparing integrated data to three different MC event generators

- Common features in data, and in all three models:
  - Peak at Δφ=π (azimuthally back-to-back)
  - Shorter and wider peak for nuclear, with larger values in tail compared to deuterium

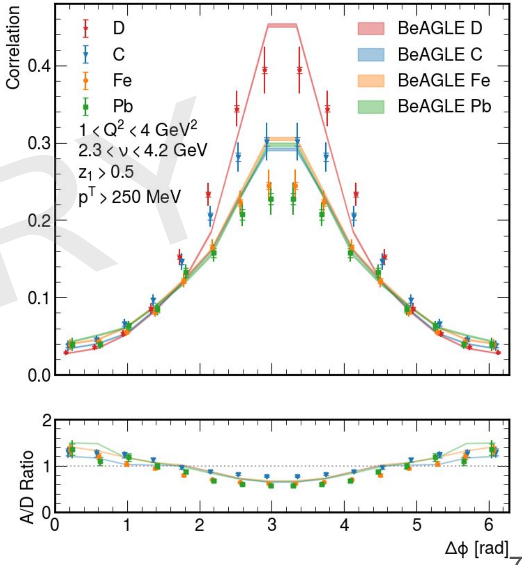
GiBUU



eHIJING

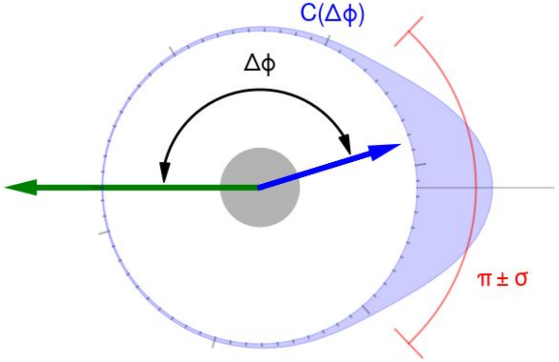


BeAGLE

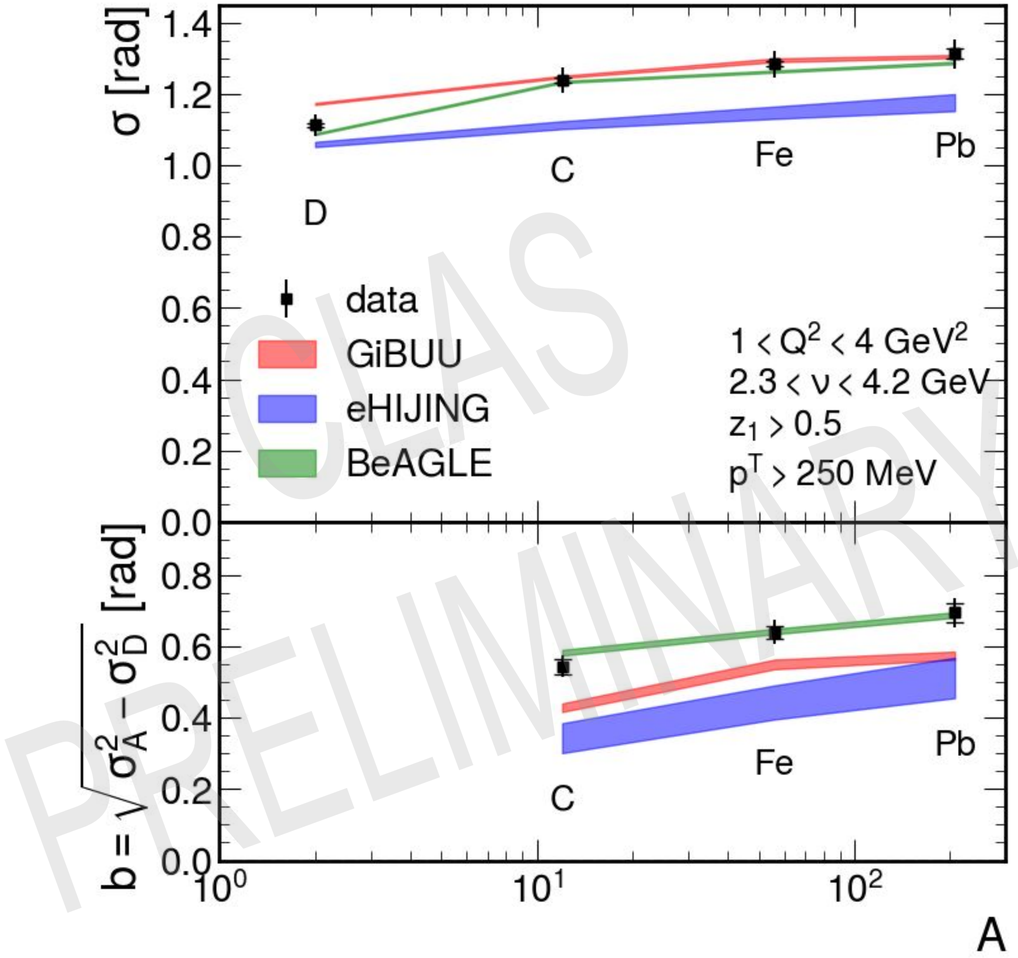


RMS widths and "broadenings"

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



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



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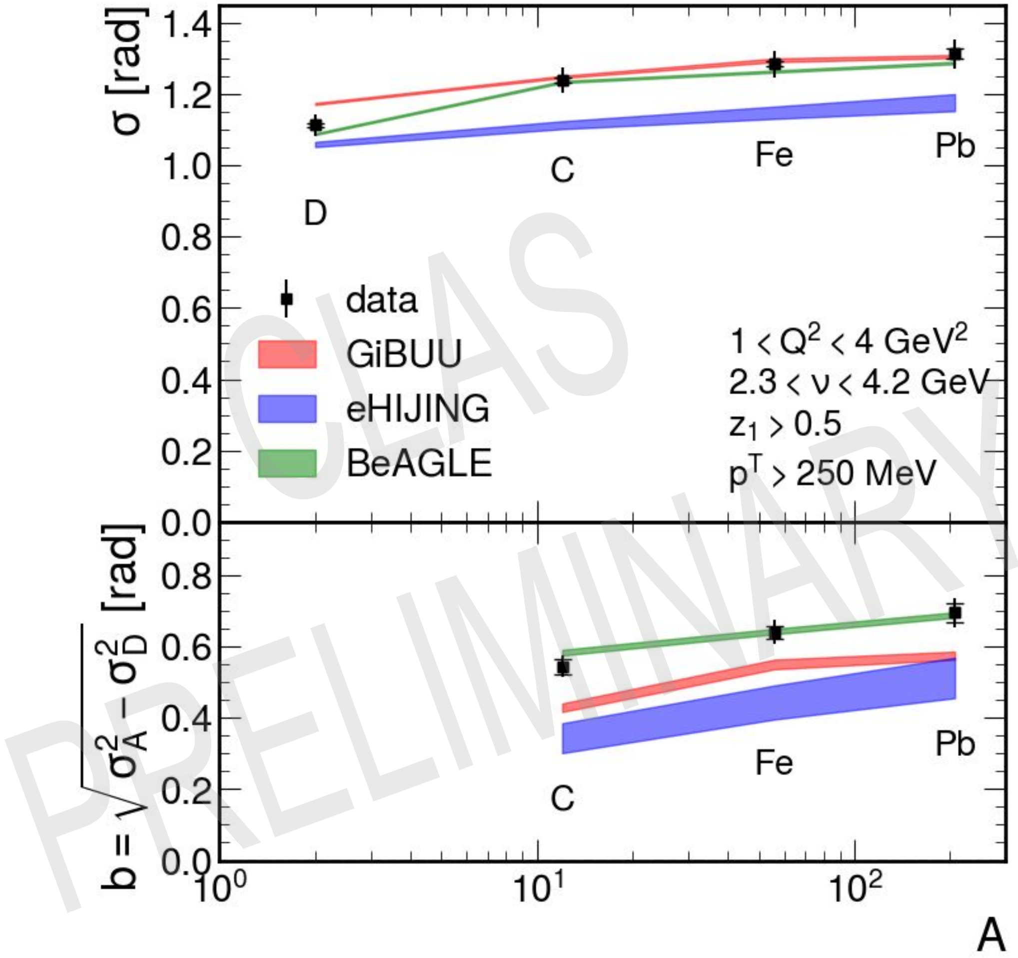
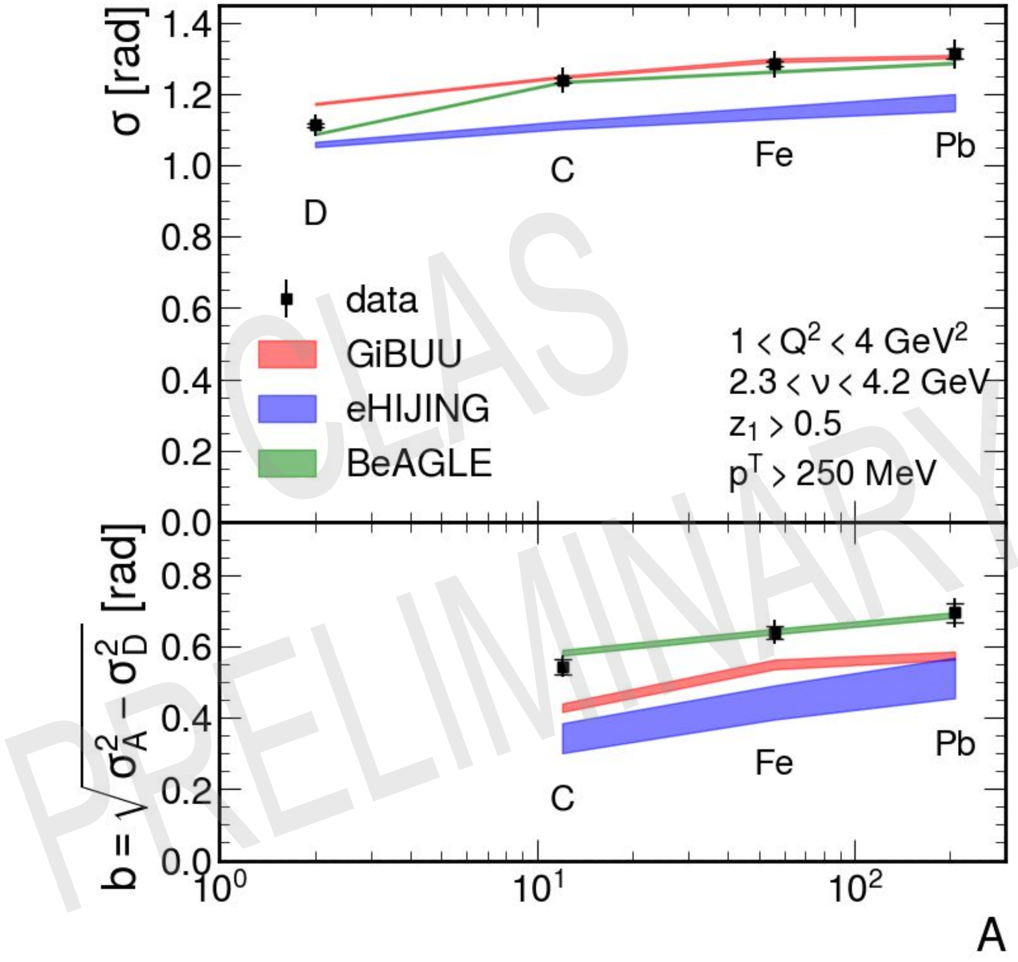
MC Event-generators

- GiBUU:
  - Main features
    - Final-state interactions
    - Absorption
    - Hadron production mechanisms
    - Pre-hadron degrees of freedom
    - Color transparency
    - Nuclear shadowing
  - Agrees with nuclear data, some discrepancy for D
  - Broadening about 20% below that of data



MC Event-generators

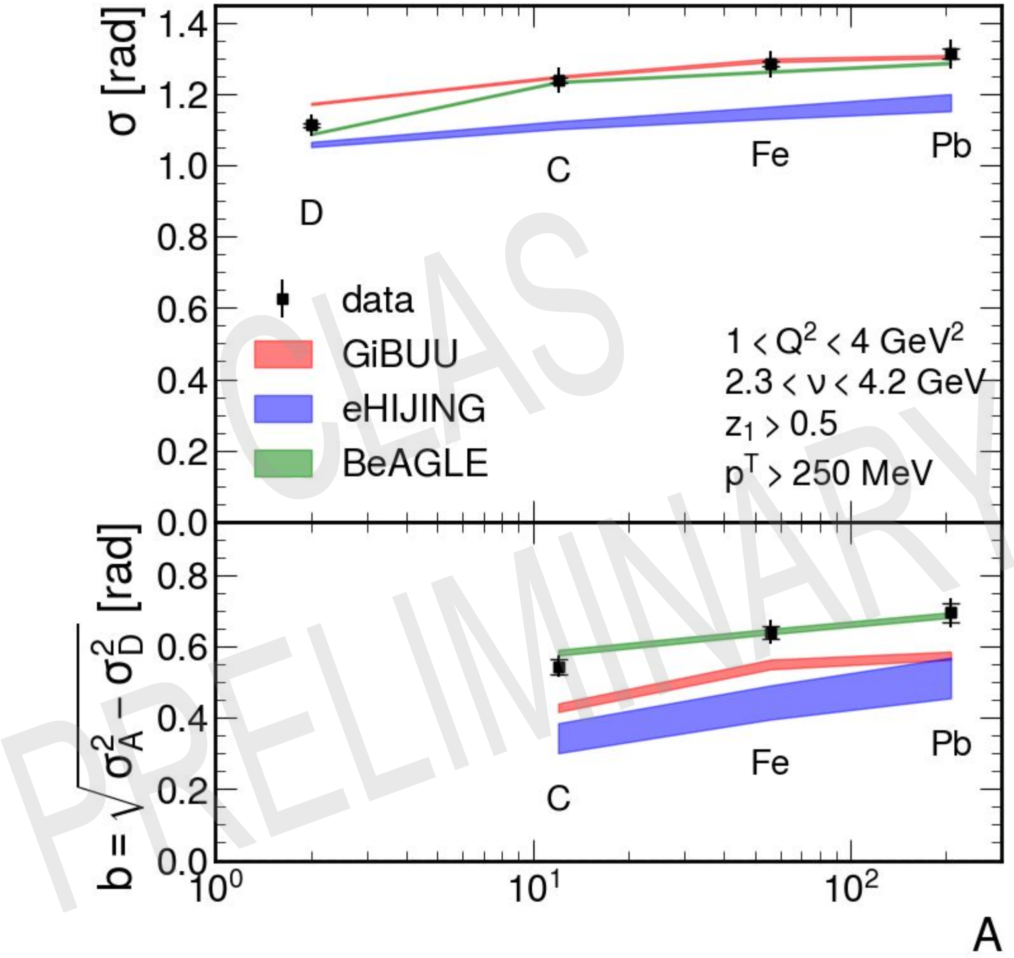
- eHIJING*
  - Features
    - Interaction between hadrons and the nuclear medium proportional to the nuclear TMD PDF of gluons.
  - Qualitatively decent agreement with data, but with quantitatively smaller σ and smaller b than in data



* arXiv:2304.10779v1

MC Event-generators

- BeAGLE*
  - Mixture of components from multiple generators
    - Primary interaction (Pythia6)
    - Nuclear remnant decay/de-excitation (FLUKA)
    - Intranuclear cascade (DPMJet)
    - Geometric density of nucleons (PyQM)
    - Nuclear parton distribution functions (LHAPDF5)
  - Overall, best agreement with data for widths for all targets

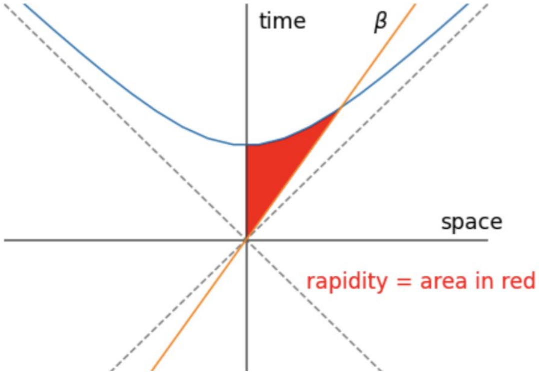


*arXiv:2204.11998

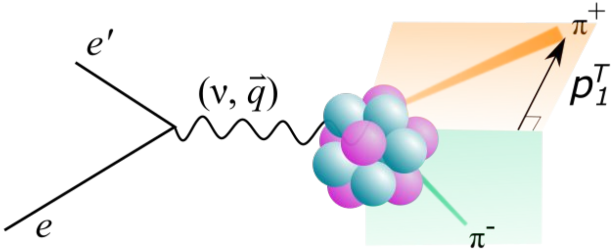
Multidimensional binning of the correlation function

Rapidity difference, ΔY

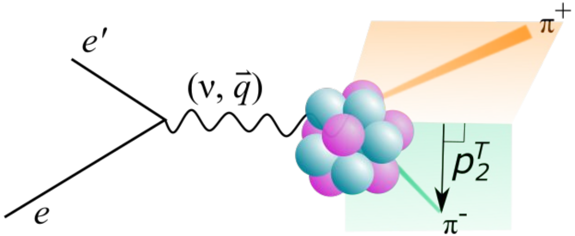
$$Y = \frac{1}{2}\ln\frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$



Transverse momentum of leading pion



Transverse momentum of sub-leading pion



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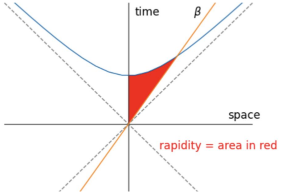
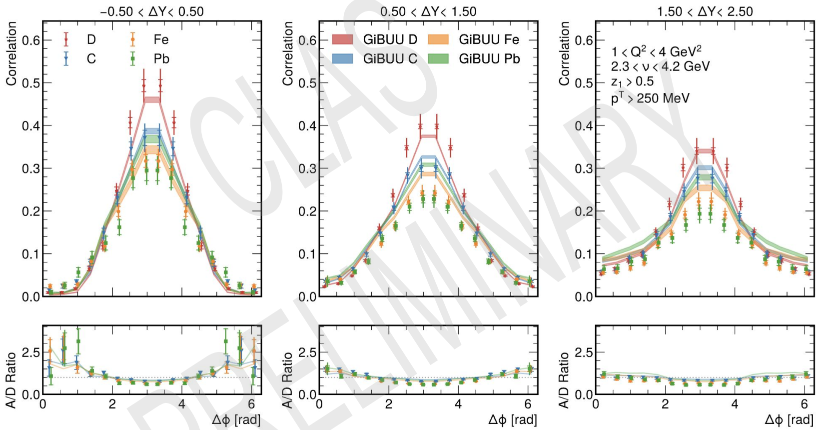
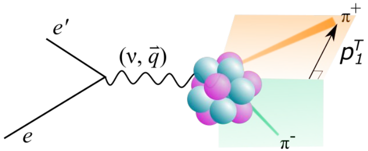
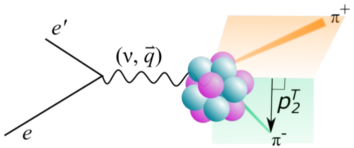
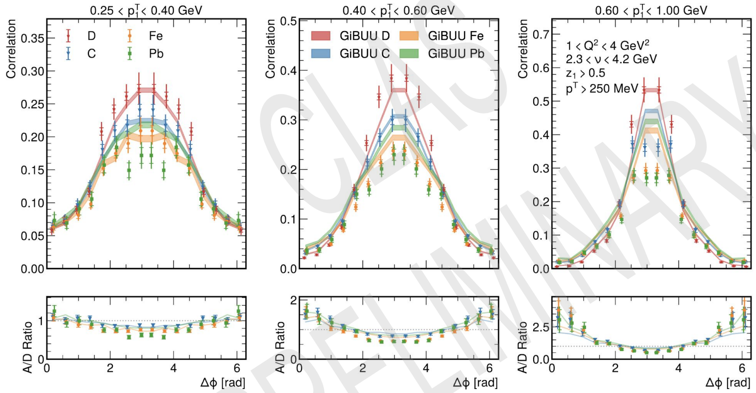
Correlations in multidimensional slices

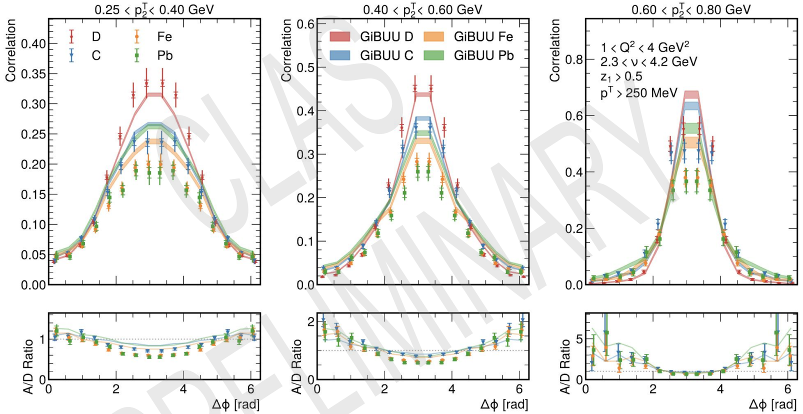






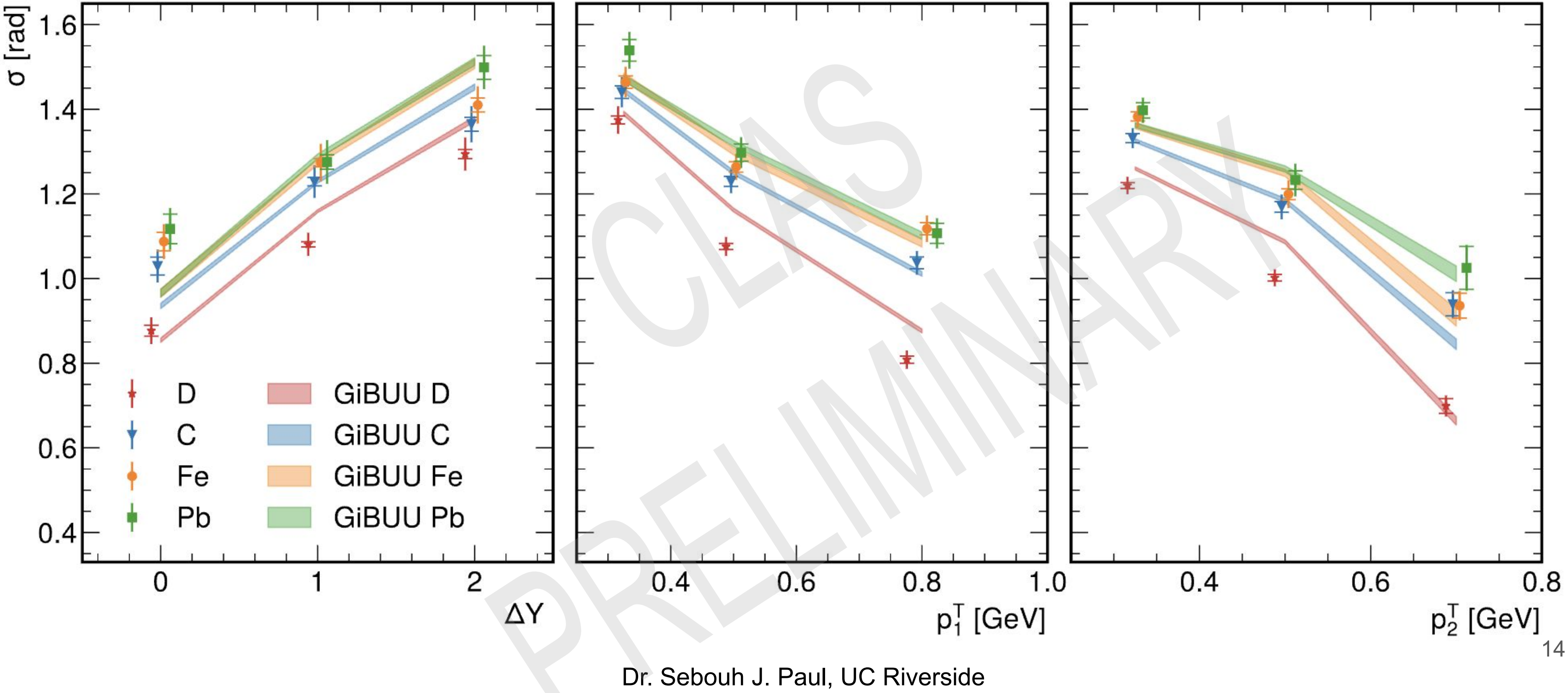






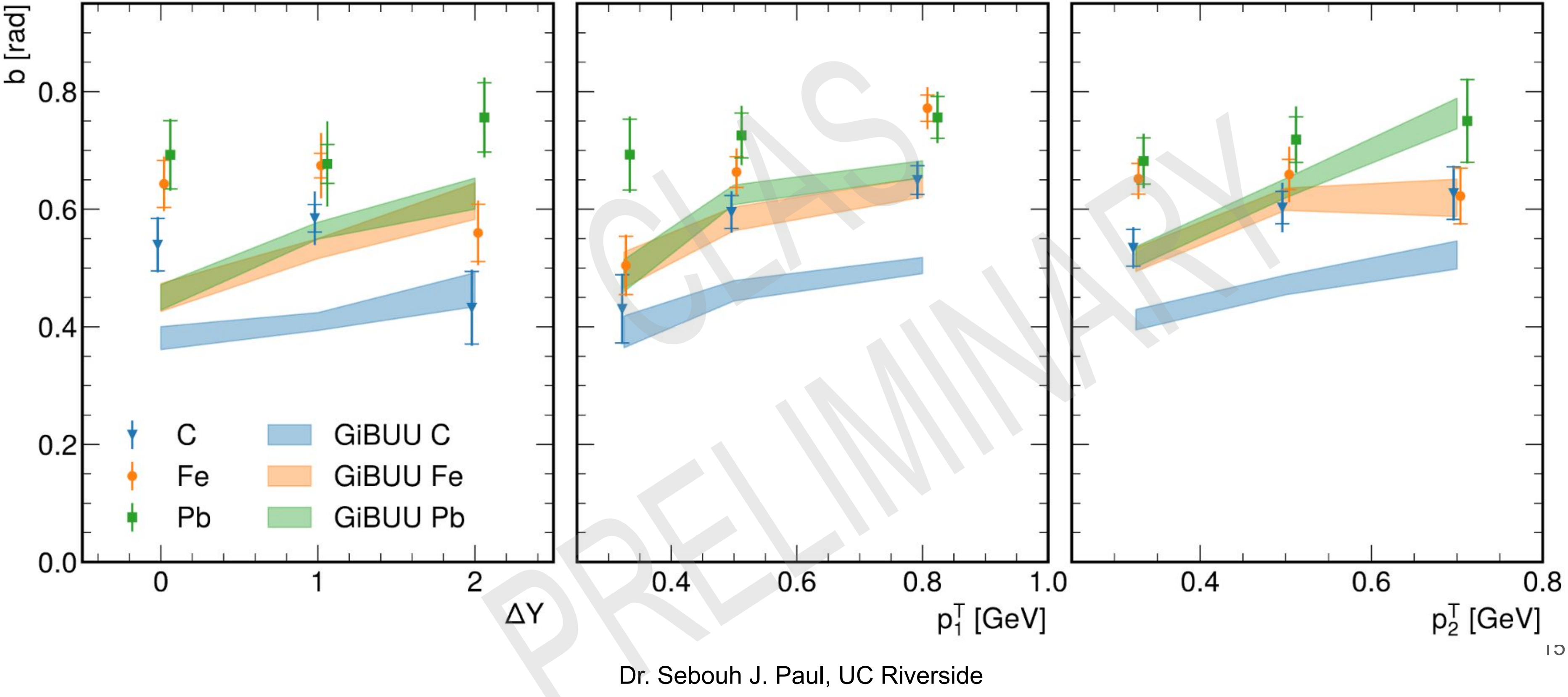
Widths of correlation functions (RMS)

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



Broadening of correlation functions

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



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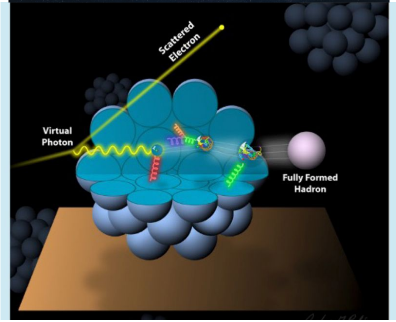
Summary

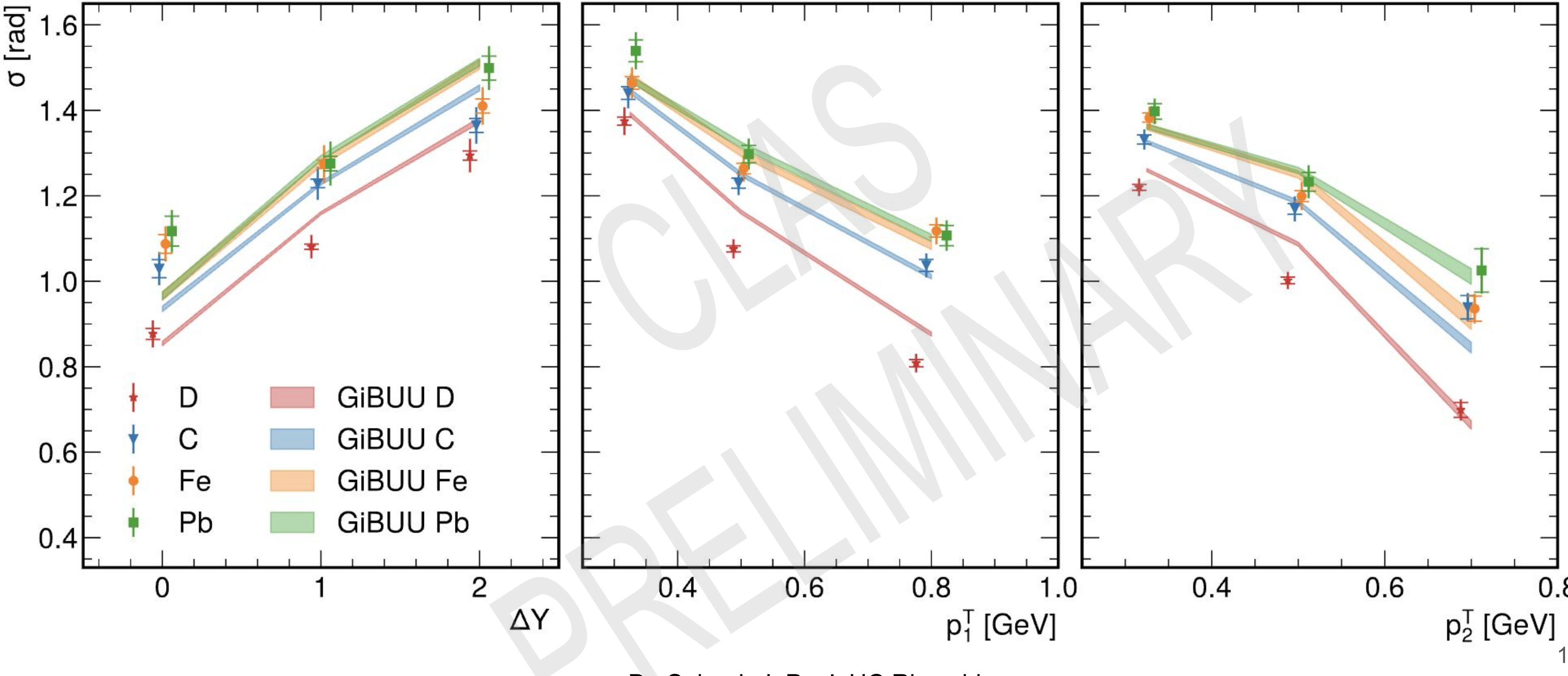
- Our di-hadron studies have been explicitly mentioned in the highlights since the previous Long-Range Plan
- Current and future analyzes will seek to answer some of the questions raised in the new LRP
  - How are the various hadrons produce in a single scattering process correlated with one another and how does hadronization change in a dense partonic environment?
  - What are the timescales of color neutralization and hadron formation?
- Drafting paper, with PRC as our target journal; we will be ready soon for ad-hoc review



Backup slides

Widths of correlation functions (RMS)

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



Broadening of correlation functions

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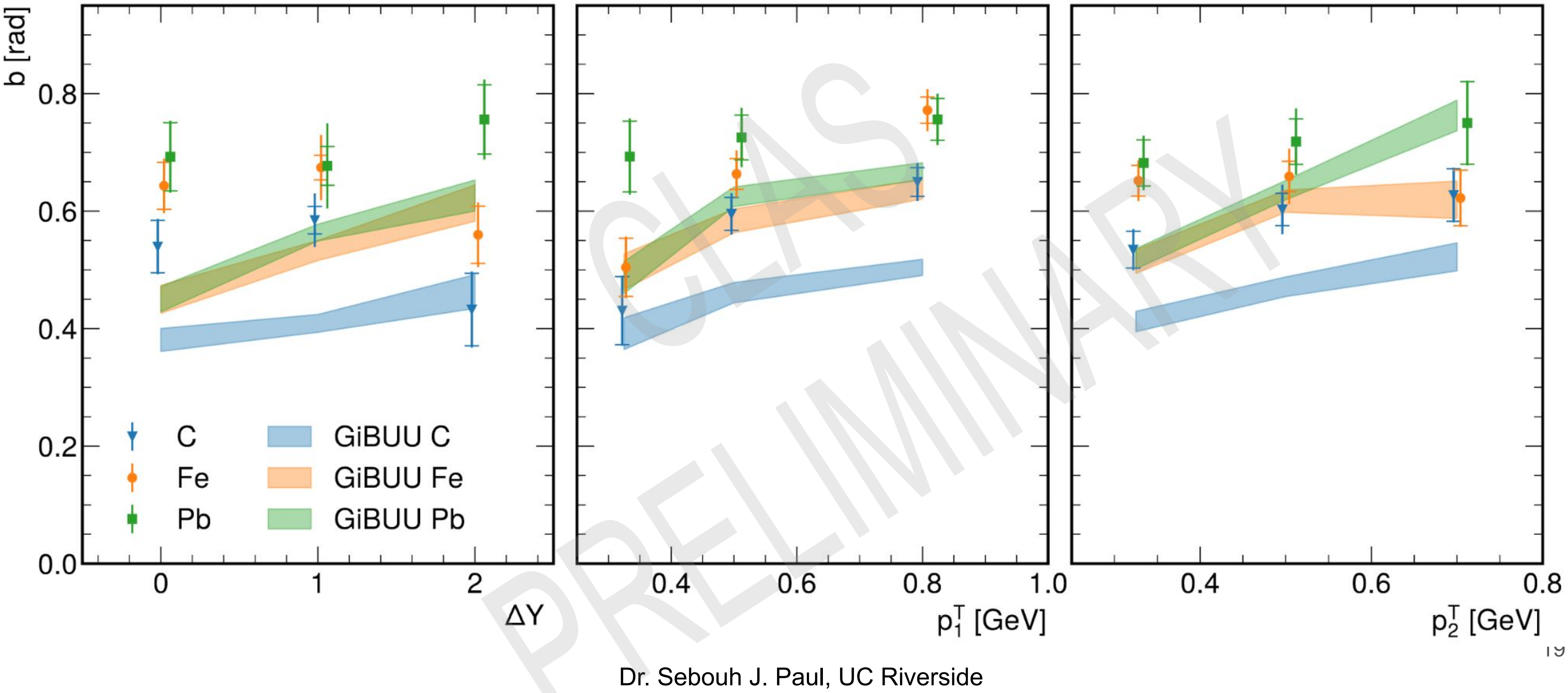

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Systematic uncertainties summary (C and R2h)

- Some systematic uncertainties are large for specific multidimensional bins

Source	$\Delta C/C$ (D)	$\Delta C/C$ (A)	corr. A vs D?	type	$\Delta R_{2h}/R_{2h}$
Statistics	1.1–38.8%	1.8–43.8%	N	p2p	2.2–52.7%
Time dependent effects	negligible	negligible	–	–	negligible
Bin migration	negligible	negligible	–	–	negligible
Endcaps	0.1–2.6%	–	–	p2p	0.1–2.6%
Endcaps (renorm)	–	0.6–0.8%	–	norm	0.6–0.8%
Particle misid.	0.0–14.3%	0.0–32.7%	Y	p2p	0.0–21.5%
Coulomb effects	negligible	negligible	–	–	negligible
Pair acceptance	6.2–6.2%	6.2–6.2%	Y	p2p	2.0–2.0%
Event selection	0.2–11.4%	0.2–11.4%	Y	p2p	0.1–21.5%
Luminosity	negligible	negligible	–	–	negligible
Trigger efficiency	negligible	negligible	–	–	negligible
Syst. subtotal	6.2–16.5%	6.3–33.7%	–	–	2.1–22.2%
Total	6.4–40.1%	6.7–47.9%	–	–	3.1–53.1%

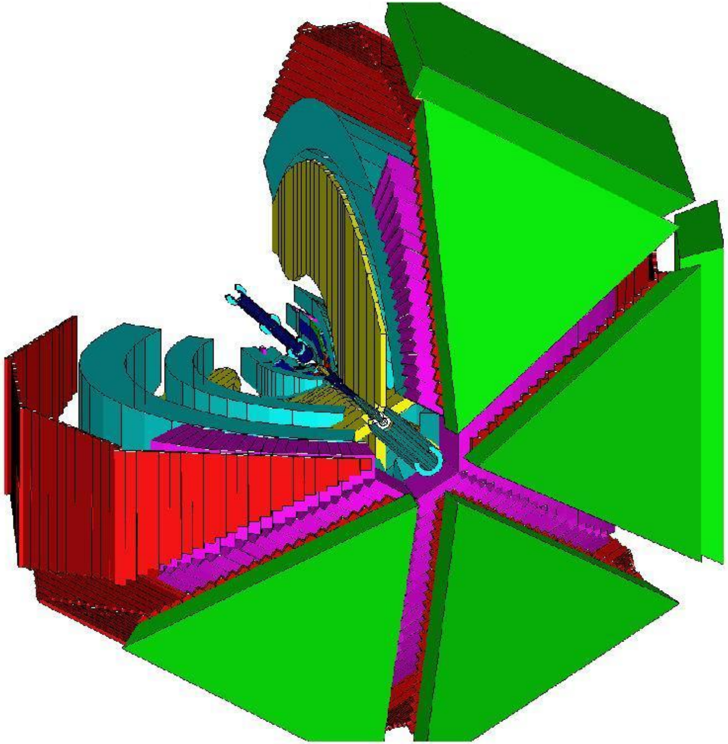
Systematic uncertainties summary (σ and b)

- Relative systematic uncertainties for σ and b are considerably smaller

Source	$\Delta\sigma/\sigma$ (D)	$\Delta\sigma/\sigma$ (A)	corr. D vs A?	$\Delta b/b$
Statistics	0.4–2.5%	0.6–4.9%	N	2.7–14.1%
Time dependent effects	negligible	negligible	–	negligible
Bin migration	negligible	negligible	–	negligible
Finite bin width	0.1–1.4%	0.0–0.7%	Y	0.4–0.7%
Endcaps	0.0–0.1%	0.0–0.0%	N	0.0–0.2%
Particle misid.	0.1–0.8%	0.0–3.0%	Y	0.3–8.9%
Coulomb effects	negligible	negligible	–	negligible
Pair acceptance	1.0–1.4%	0.9–1.2%	Y	1.4–1.4%
Event selection	0.9–2.5%	0.9–2.5%	Y	0.3–3.8%
Luminosity	negligible	negligible	–	negligible
Trigger efficiency	negligible	negligible	–	negligible
Syst. subtotal	1.9–3.2%	2.0–3.7%	Y	2.4–9.2%
Total	2.0–3.8%	2.2–5.4%	Y	4.5–14.8%

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



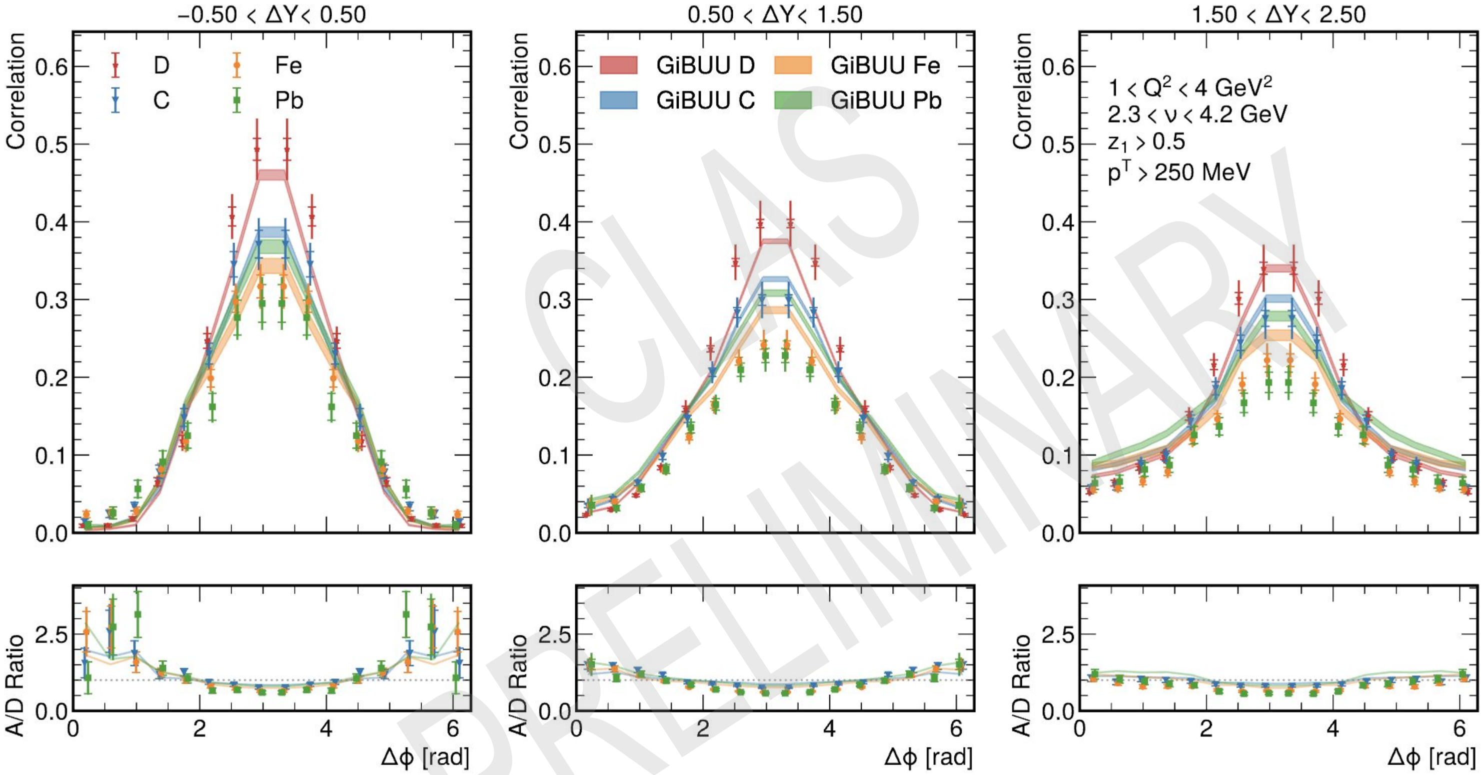
*NIM A 592 (2008) 218– 223

Rapidity dependence of C(ΔΦ)

$\Delta Y = Y_1 - Y_2$

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

- Large discrepancy between data and model at ΔY, Δφ near 0



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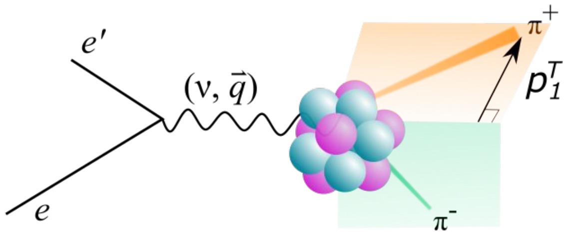
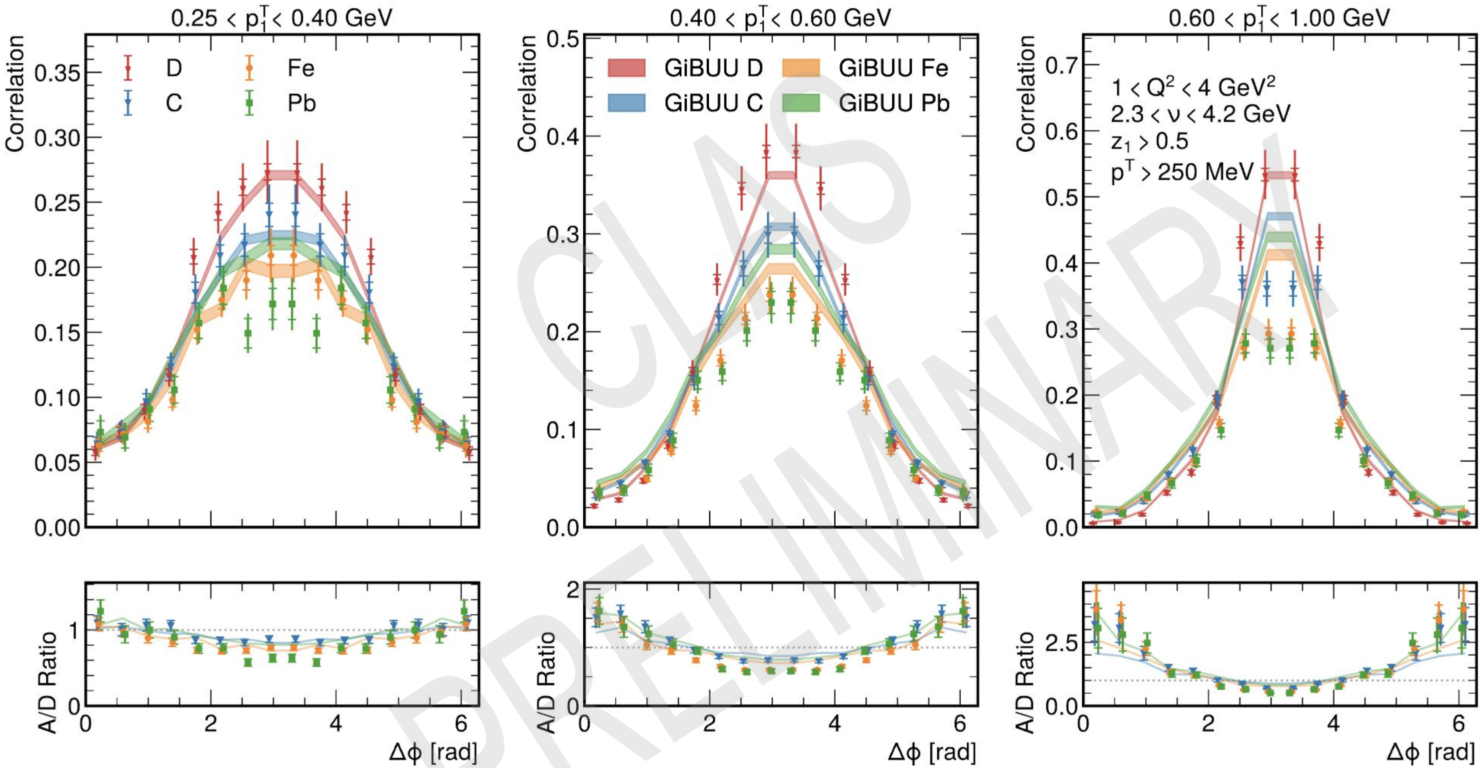
Transverse momentum of leading pion

- Narrower correlations with larger p_1^T





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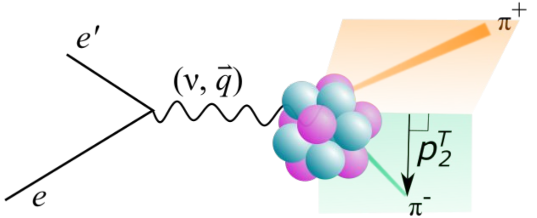
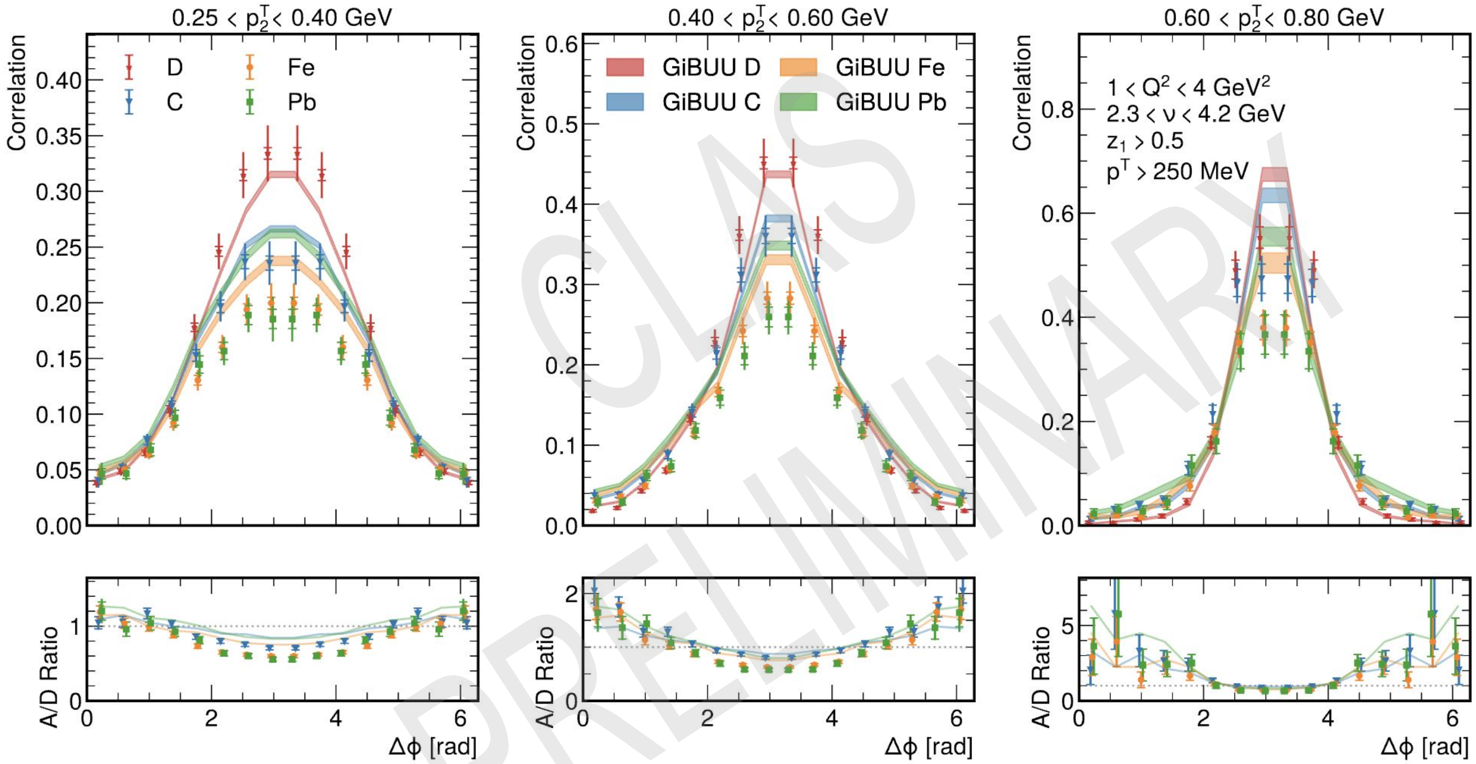
Transverse momentum of sub-leading pion



- Narrower correlations with larger p_2^T as well.



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Previous results focused on A/D ratios

PHYSICAL REVIEW LETTERS

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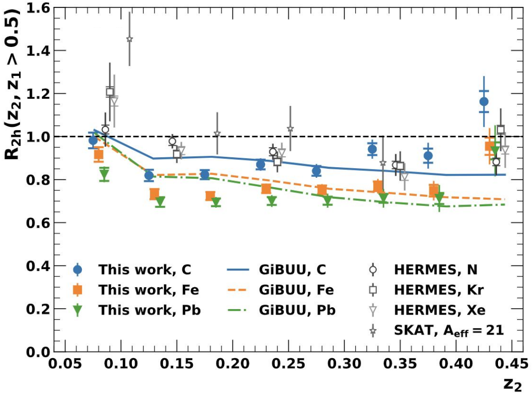
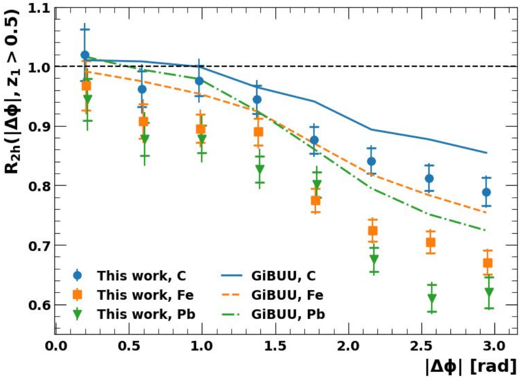
$$R_{2h} = \frac{(N_{2h}/N_h)^A}{(N_{2h}/N_h)^D} \equiv \frac{C_A}{C_D}$$

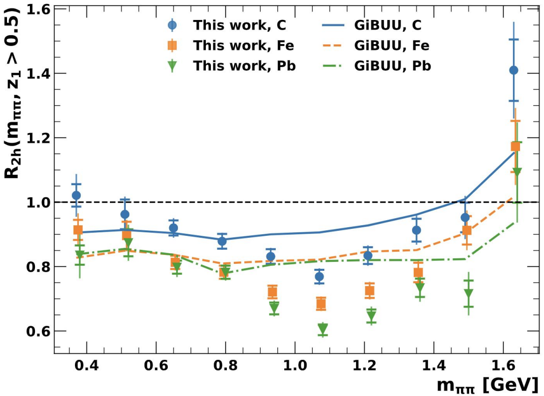
Observation of Azimuth-Dependent Suppression of Hadron Pairs in Electron Scattering off Nuclei

S. J. Paul *et al.* (CLAS Collaboration)

Phys. Rev. Lett. **129**, 182501 – Published 25 October 2022

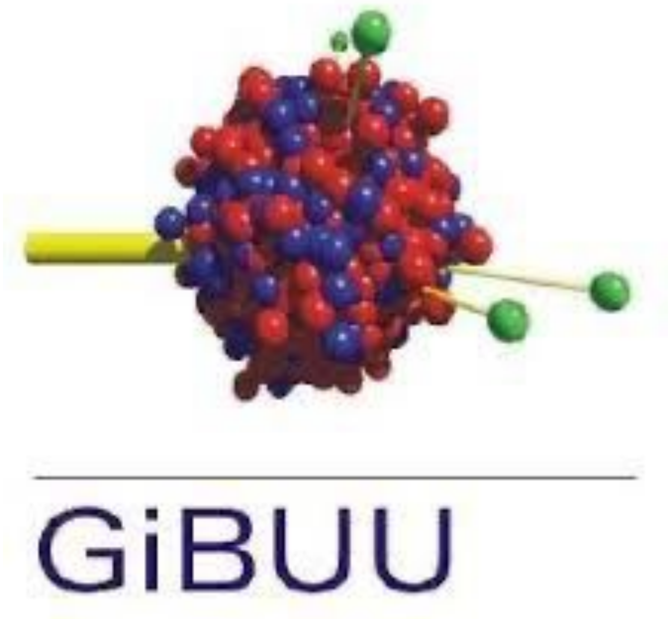






GiBUU model

- State-of-the-art transport model which includes the following ingredients:
  - Final-state interactions
  - Absorption
  - Hadron production mechanisms
  - Pre-hadron degrees of freedom
  - Color transparency
  - Nuclear shadowing



Event generators

GiBUU

- State-of-the-art transport model which includes the following ingredients:
  - Final-state interactions
  - Absorption
  - Hadron production mechanisms
  - Pre-hadron degrees of freedom
  - Color transparency
  - Nuclear shadowing

eHIJING (electron Heavy-Ion Jet INteraction Generator)

- New event generator
  - Has been compared with other CLAS, HERMES and EMC measurements