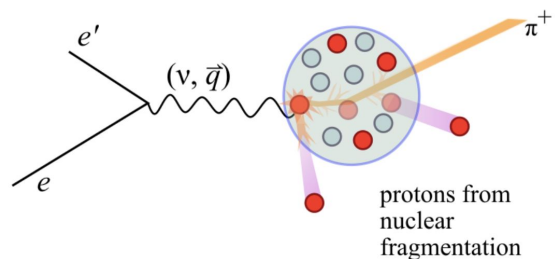


Pion-Proton Correlations in eA Scattering



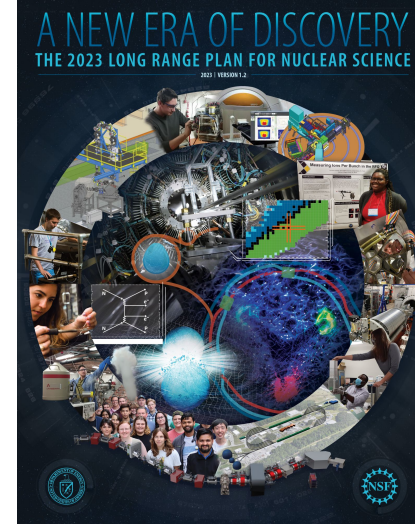
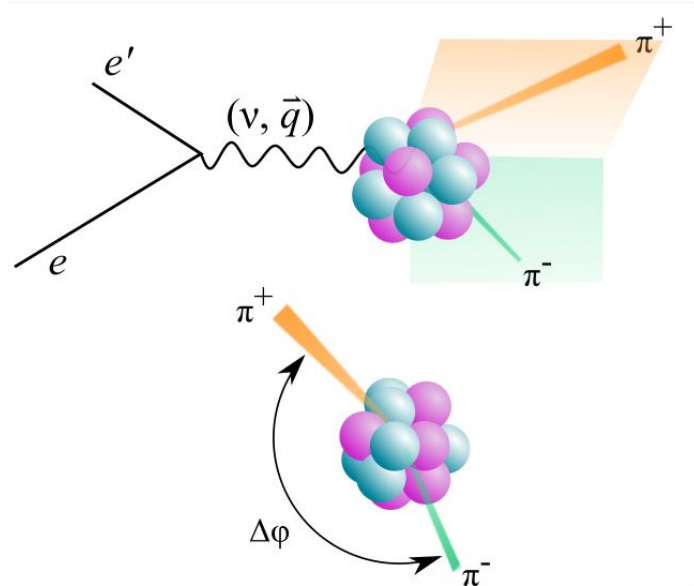
Dr. Sebouh Paul

Florida International University

11/18/2025

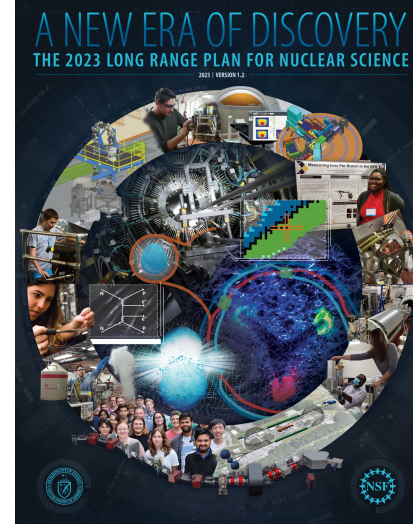
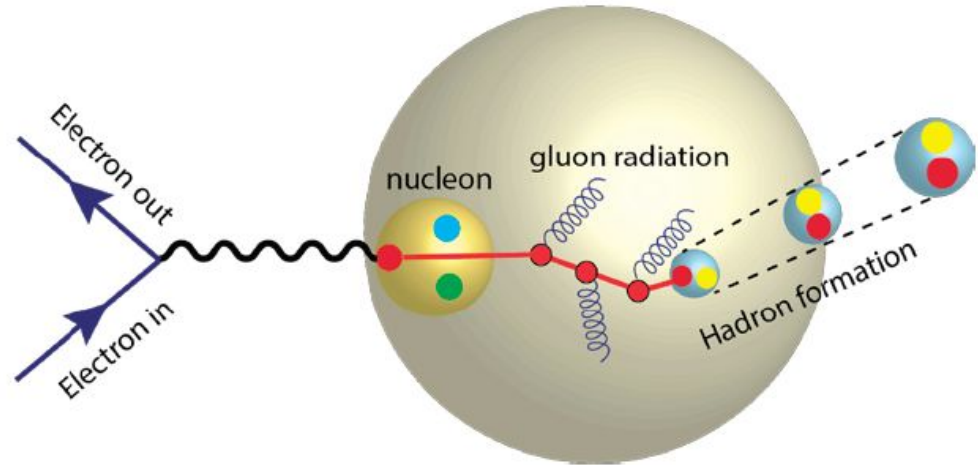


How are the various hadrons produced in a single scattering process correlated with one another...



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

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



Previous analyses: di-pion production in nuclei

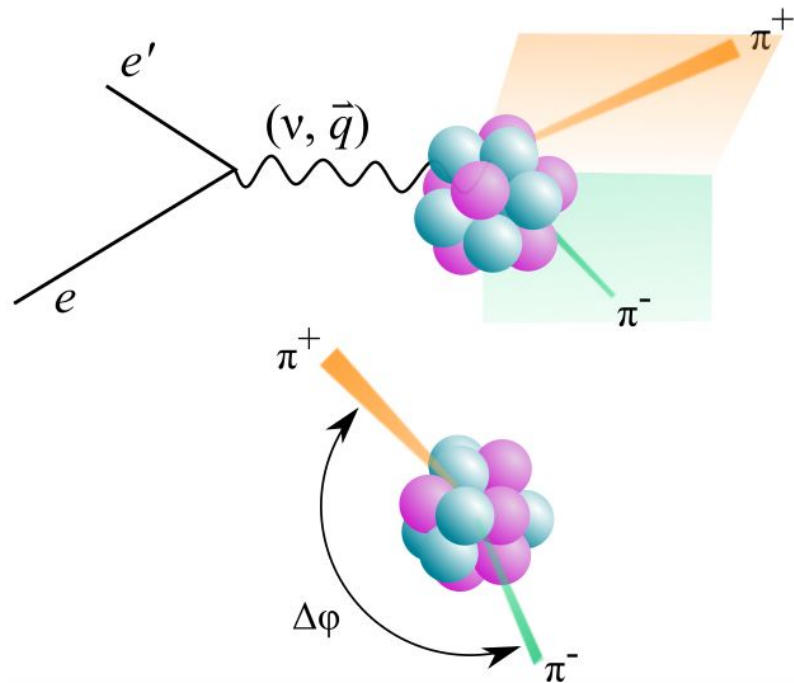
- Double ratios:

- Phys. Rev. Lett. 129, 182501 (2022)

$$R = \frac{((dN_{e'\pi\pi}/dz_2)/N_{e'\pi})^A}{((dN_{e'\pi\pi}/dz_2)/N_{e'\pi})^D}$$

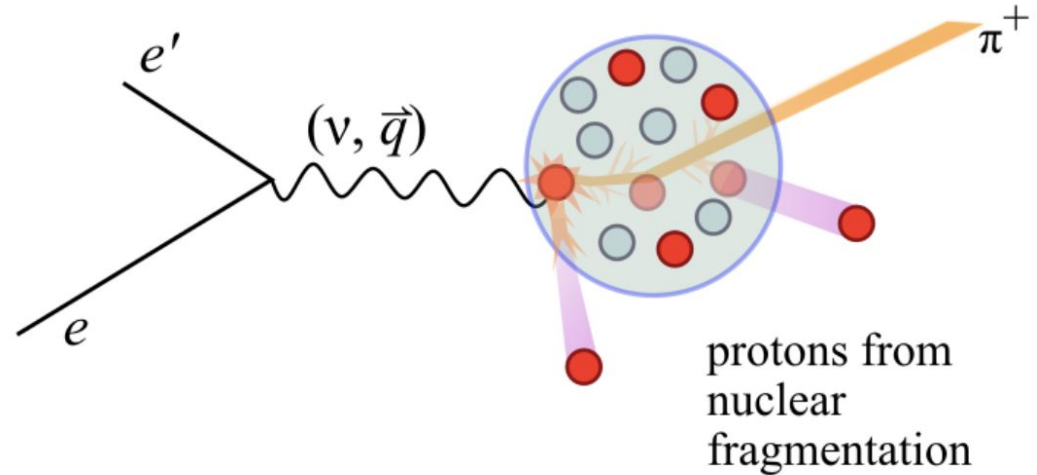
- Correlation functions:

- Phys. Rev. C 111, 035201 (2025)
- Measured distribution of the azimuthal separation between charged pions



A new event topology: πp

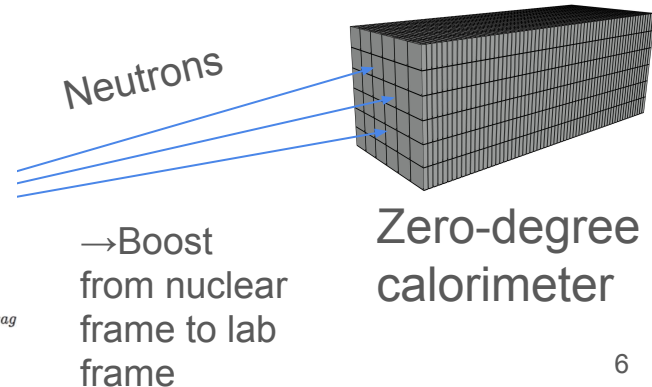
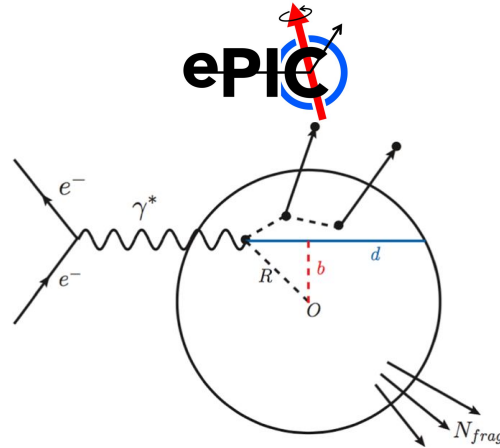
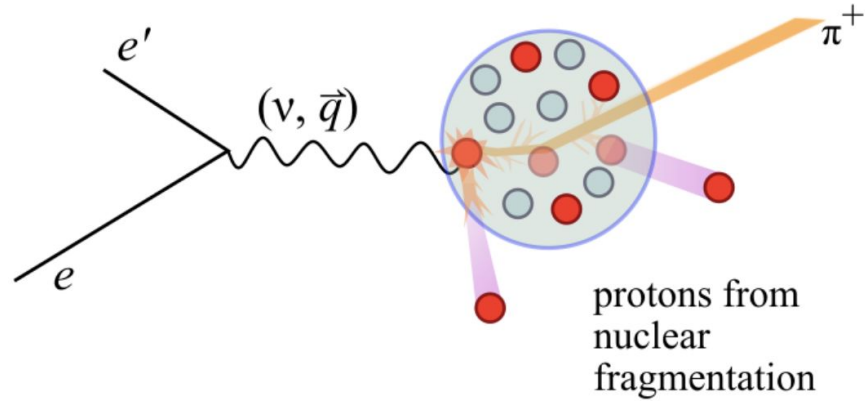
- Electron with DIS kinematics
 - $Q^2 > 1 \text{ GeV}^2$
 - $W > 2 \text{ GeV}$
 - $2.3 < \nu < 4.2 \text{ GeV}$
- High energy π^+
 - $z \equiv E_h/\nu > 0.5$
- A secondary proton
 - Originates from the fragmentation of the nucleus



“Slow” knockout protons

- “Slow” knockout protons in this analysis are analogous to “slow neutrons” in planned studies with the EIC’s Zero-Degree Calorimeter
 - Slow nucleons in an event can proxy the path length of the cascade through the nucleus*
 - Measurements of protons at JLab can feed into models used for the EIC, test MC generators.

Jefferson Lab



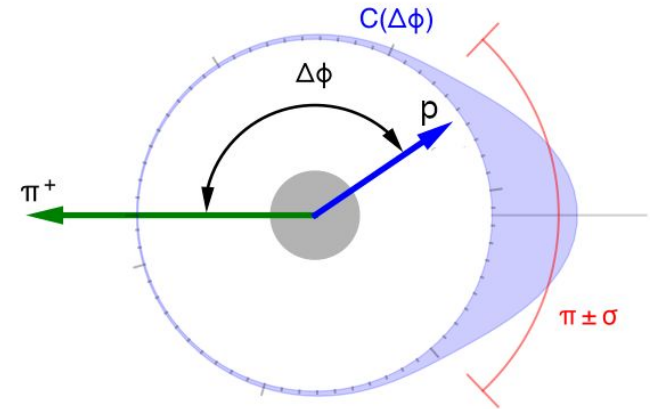
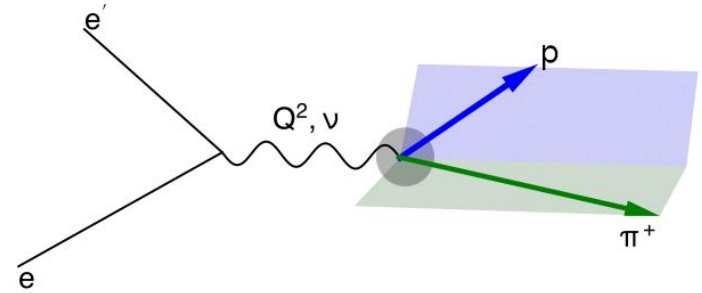
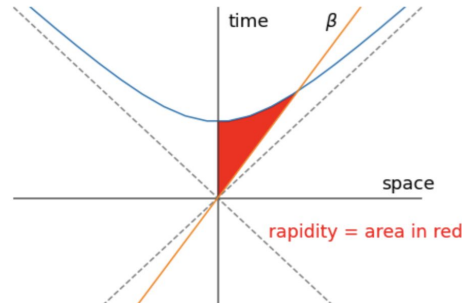
Correlation function

Normalized distribution of the separation in azimuth and rapidity between the two hadrons

$$C(\Delta\phi, \Delta Y) \equiv C_0 \times \frac{1}{N_{e'\pi}} \frac{dN_{e'\pi p}}{d\Delta\phi d\Delta Y}$$

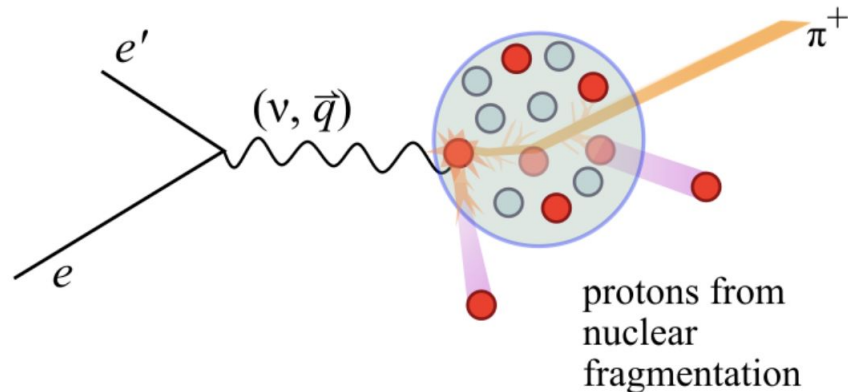
$$\Delta Y = Y_{\pi^+} - Y_p$$

$$Y = \frac{1}{2} \log \frac{E + p_z}{E - p_z}$$



Review status

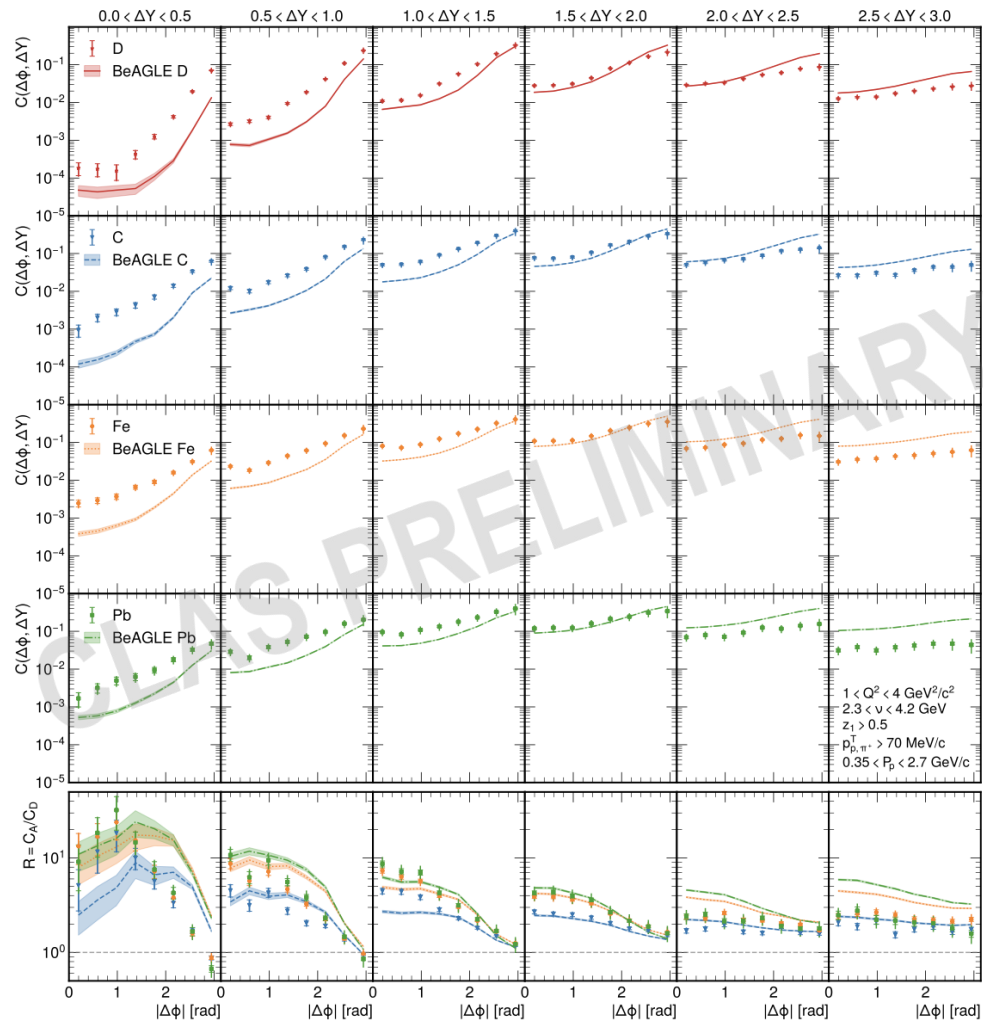
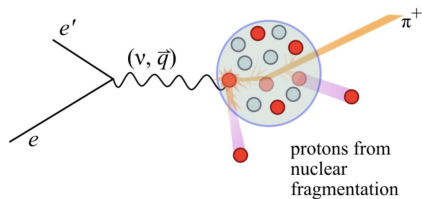
- Ad-hoc review ended last month
- Collaboration-wide review in progress; ends this Sunday
- To be followed by author check
- And then submitted to arXiv and Phys. Lett. B. for publication.



Measured correlation functions

$$C(\Delta\phi, \Delta Y) \equiv C_0 \times \frac{1}{N_{e'\pi}} \frac{dN_{e'\pi p}}{d\Delta\phi d\Delta Y}$$

- Peaks at $\Delta\phi \approx \pi$, $1.0 < \Delta Y < 1.5$



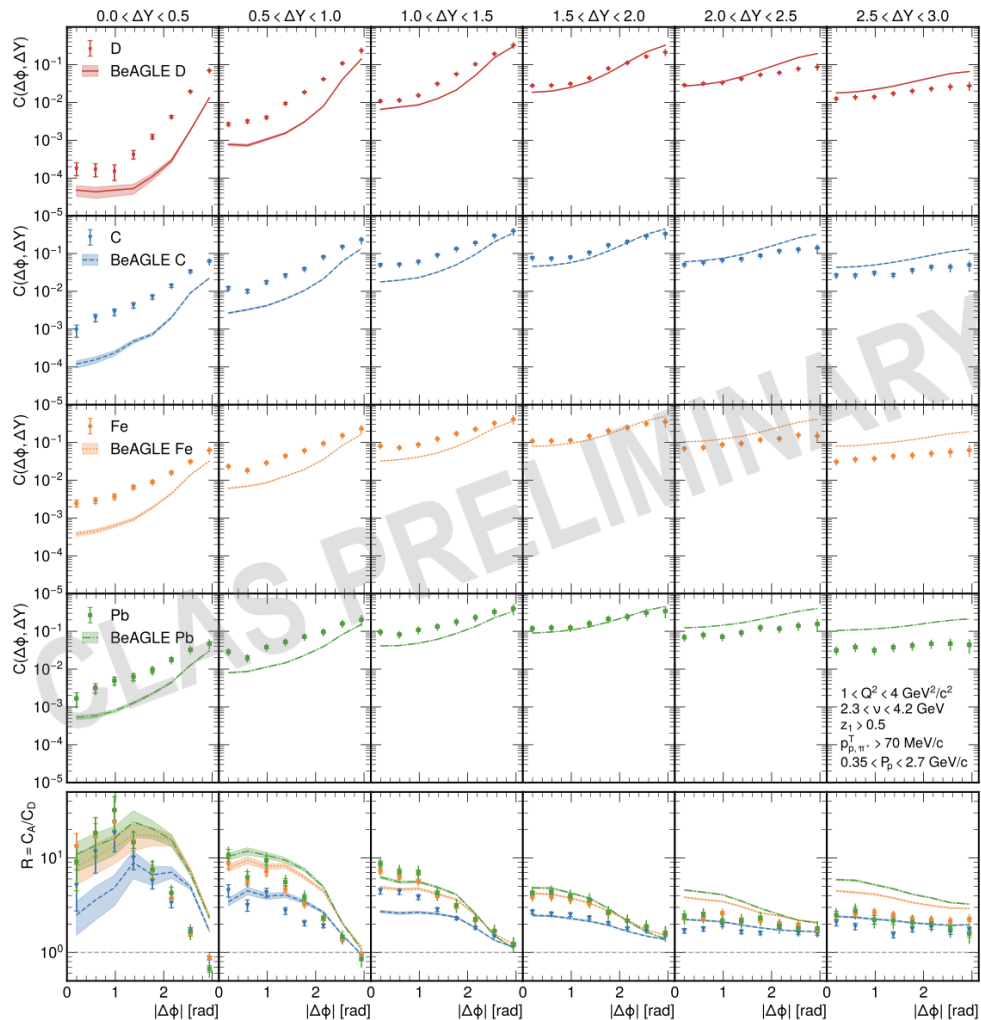
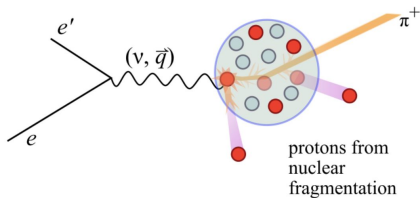
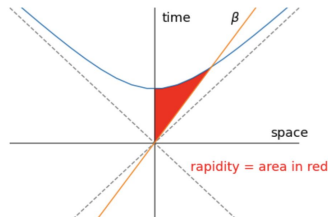
Measured correlation functions

$$C(\Delta\phi, \Delta Y) \equiv C_0 \times \frac{1}{N_{e'\pi}} \frac{dN_{e'\pi p}}{d\Delta\phi d\Delta Y}$$

- Correlation function has wider peak at larger ΔY

$$\Delta Y = Y_{\pi^+} - Y_p$$

$$Y = \frac{1}{2} \log \frac{E + p_z}{E - p_z}$$



Measured correlation functions

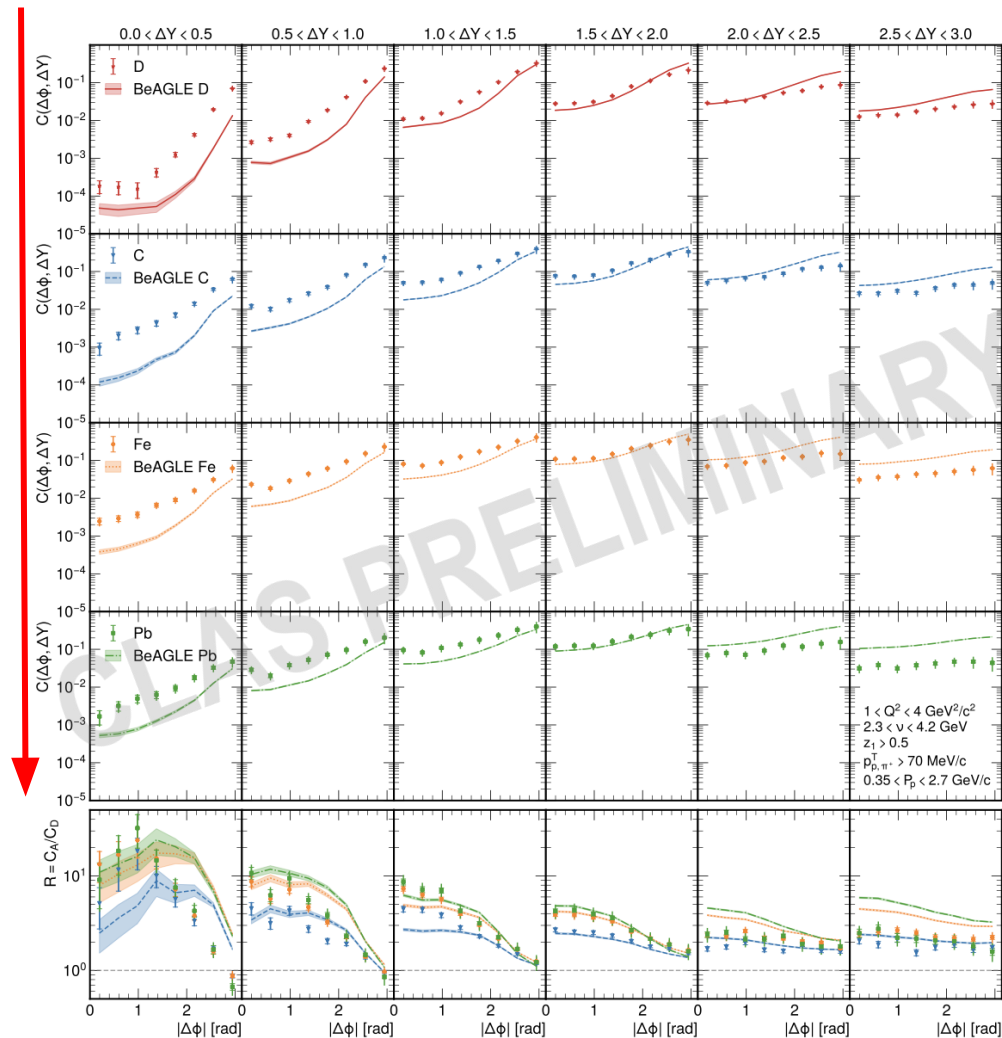
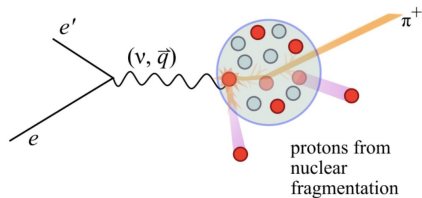
$$C(\Delta\phi, \Delta Y) \equiv C_0 \times \frac{1}{N_{e'\pi}} \frac{dN_{e'\pi p}}{d\Delta\phi d\Delta Y}$$

- Also, wider peak for heavier targets

Relative sizes of nuclei



$$r \propto A^{1/3}$$



Measured correlation functions

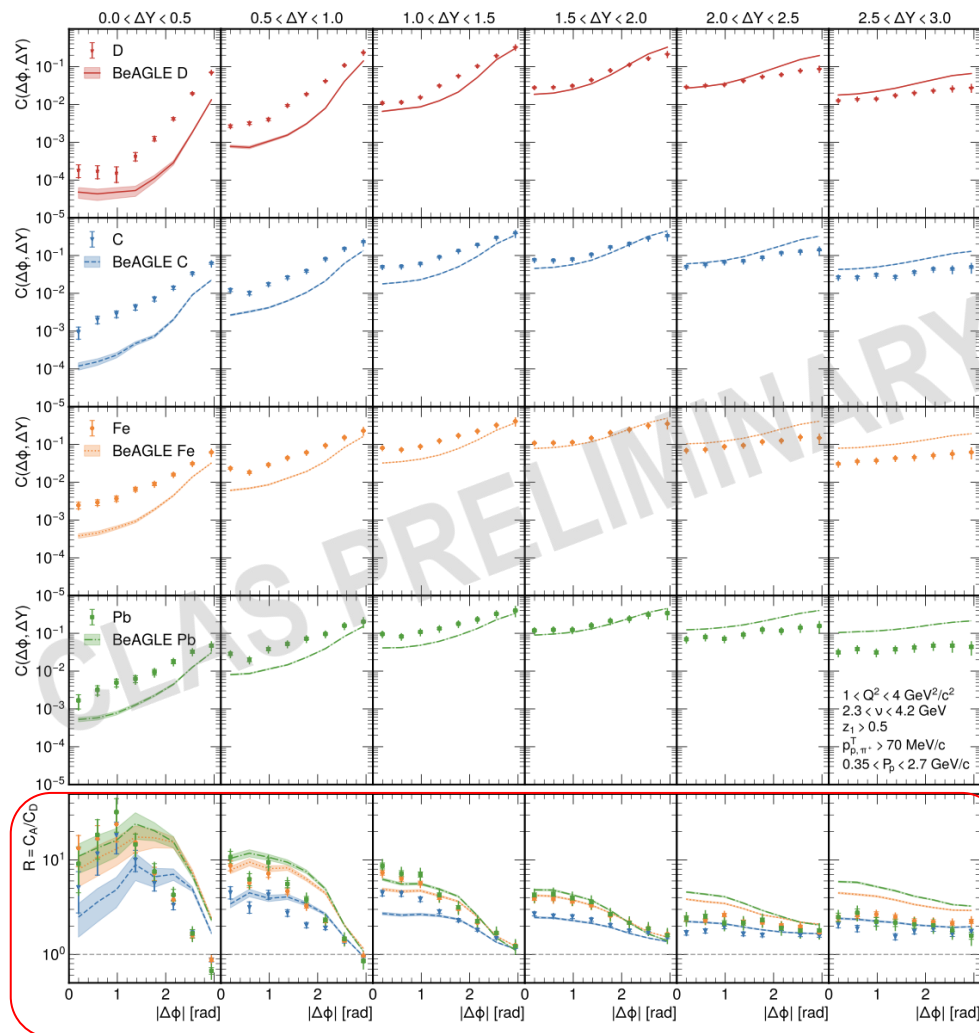
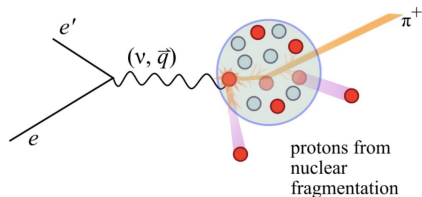
$$C(\Delta\phi, \Delta Y) \equiv C_0 \times \frac{1}{N_{e'\pi}} \frac{dN_{e'\pi p}}{d\Delta\phi d\Delta Y}$$

- A/D ratio is >1 for most bins, more protons per pion in heavier nuclei

Relative sizes of nuclei



$$r \propto A^{1/3}$$

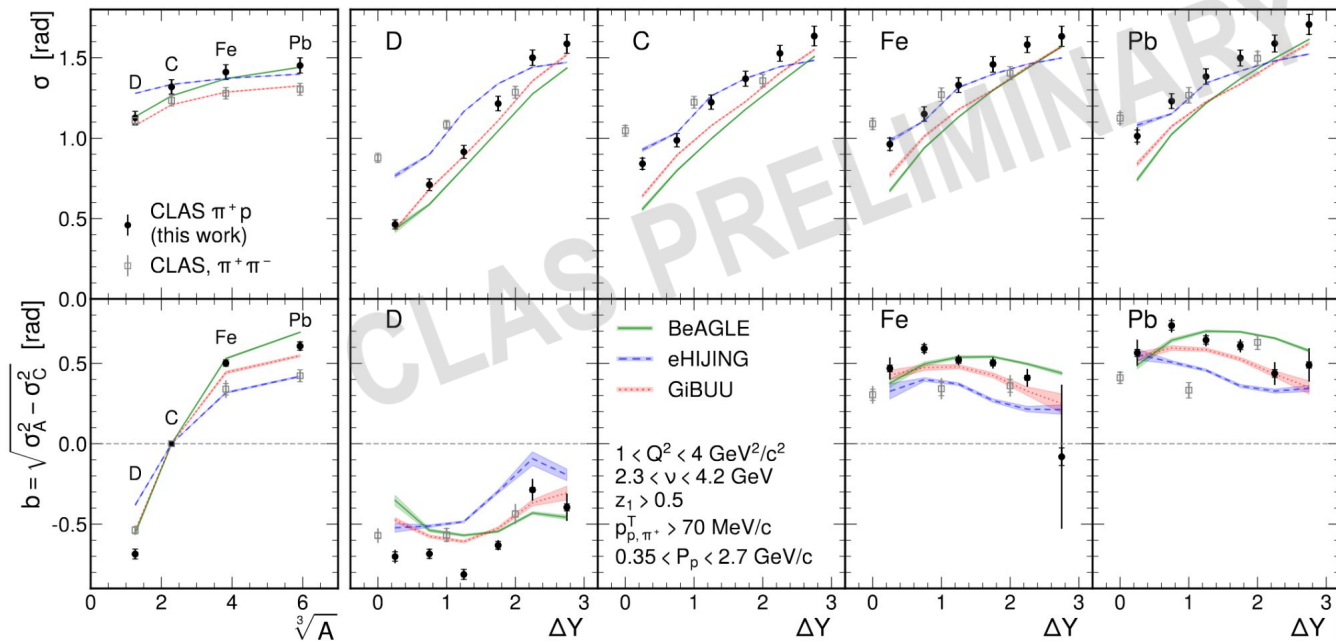


RMS widths and broadenings

- RMS widths increase with both nuclear size and ΔY
- πp channel more sensitive to ΔY and A than the $\pi\pi$ channel.

$$b = \pm \sqrt{\sigma_A^2 - \sigma_C^2}$$

$$\sigma = \frac{\sum_{i \in \text{bins}} (\Delta\phi_i - \pi)^2 C(\Delta\phi_i)}{\sum_{i \in \text{bins}} C(\Delta\phi_i)}$$

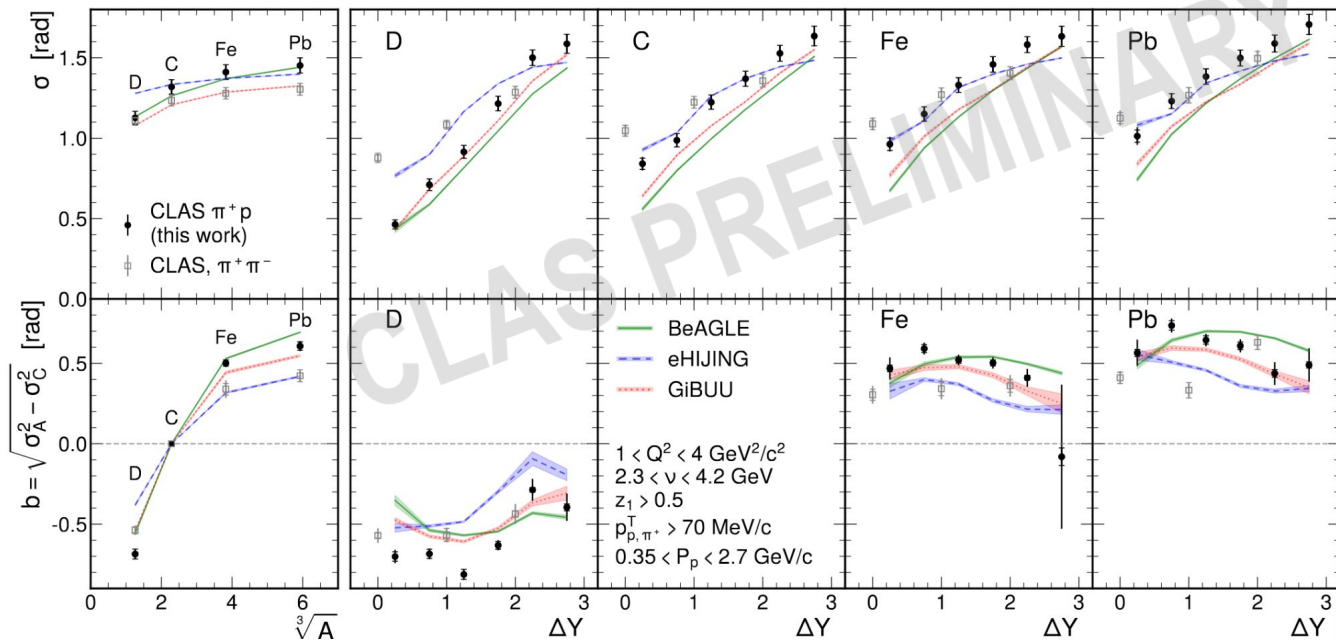


RMS widths and broadenings

- General trends in data reproduced by BeAGLE, eHIJING and GiBUU models
- These data could be used in future global fits for further fine-tuning of the parameters of these models

$$b = \pm \sqrt{\sigma_A^2 - \sigma_C^2}$$

$$\sigma = \frac{\sum_{i \in \text{bins}} (\Delta\phi_i - \pi)^2 C(\Delta\phi_i)}{\sum_{i \in \text{bins}} C(\Delta\phi_i)}$$



BeAGLE: <https://doi.org/10.1103/PhysRevD.106.012007>

eHIJING: <https://doi.org/10.1103/PhysRevD.110.034001>

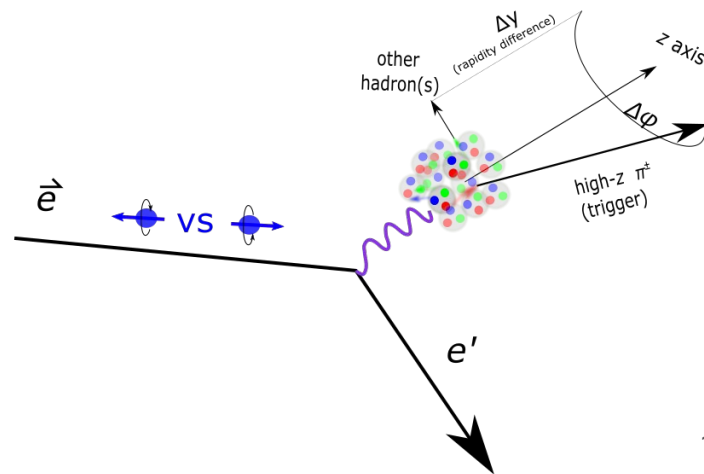
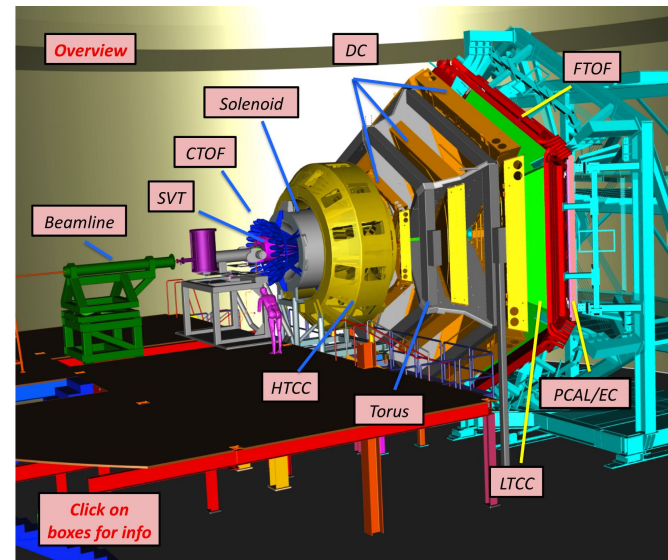
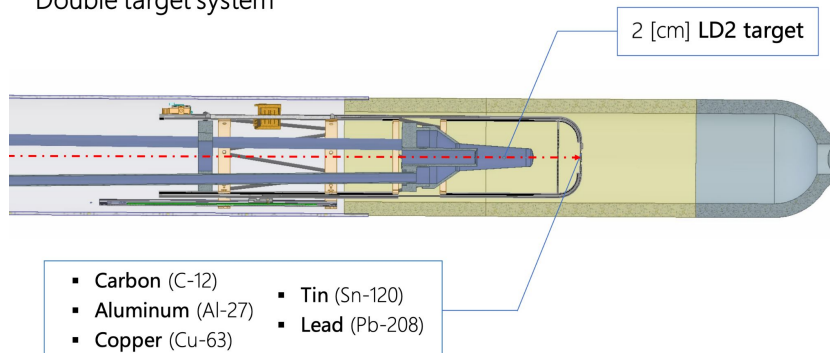
GiBUU: <https://doi.org/10.1016/j.physrep.2011.12.001>

Follow-up measurements with upgraded CLAS12 (Run Group E)

These di-hadron measurements can be extended using recent measurements with

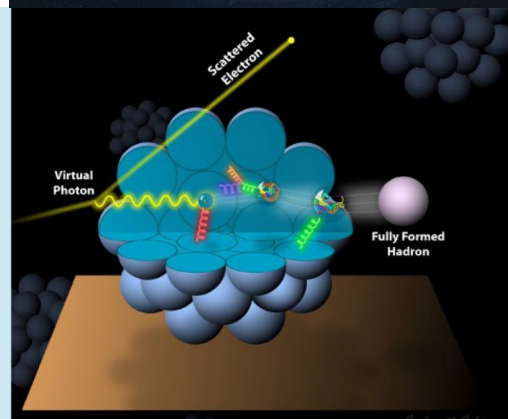
- Higher luminosity
- Higher beam energy
- Polarized electron beam
 - Can measure beam-spin asymmetries
- Larger variety of targets

Double target system



Summary

- Di-hadron correlations represents a new tool to explore how hadronization is affected by nuclei
- Current and future analyzes with RGE will seek to answer some of the questions raised in the 2023 LRP
 - 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?
 - What are the timescales of color neutralization and hadron formation?
- πp channel more sensitive to nuclear size and rapidity separation than the $\pi\pi$ channel.
- πp correlation analysis is close to the end of collab-wide review.



Backup slides

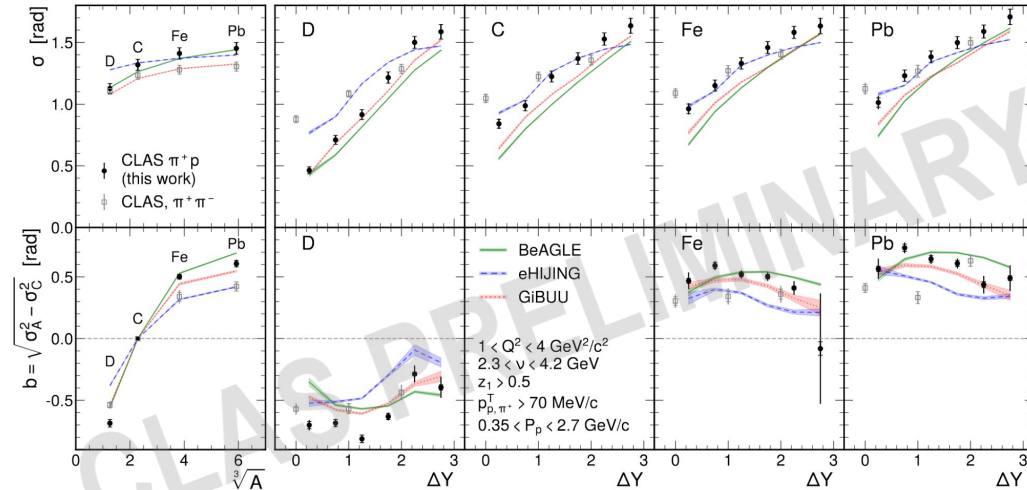
Systematic uncertainties

- Determined bin-by-bin.
- Median syst. uncertainty: $\sim 18\%$

Source	$\Delta C/C$ (D)	$\Delta C/C$ (A)	corr. A vs D	type	$\Delta R/R$
Statistics	1–44%	2–41%	N	p2p	2–51%
Endcaps	0–11%	–	–	p2p	0–11%
Particle misid.	0–21%	6–37%	Y	p2p	6–21%
Pair acceptance	15%	15%	Y	p2p	0%
Event selection	0–7%	0–7%	Y	p2p	0%
Bin migration	negligible	negligible	–	–	negligible
Time dependent effects	negligible	negligible	–	–	negligible
Luminosity	negligible	negligible	–	–	negligible
Trigger efficiency	negligible	negligible	–	–	negligible
Syst. subtotal	15–27%	16–41%	–	–	6–21%
Total	15–47%	17–46%	–	–	7–54%

Models

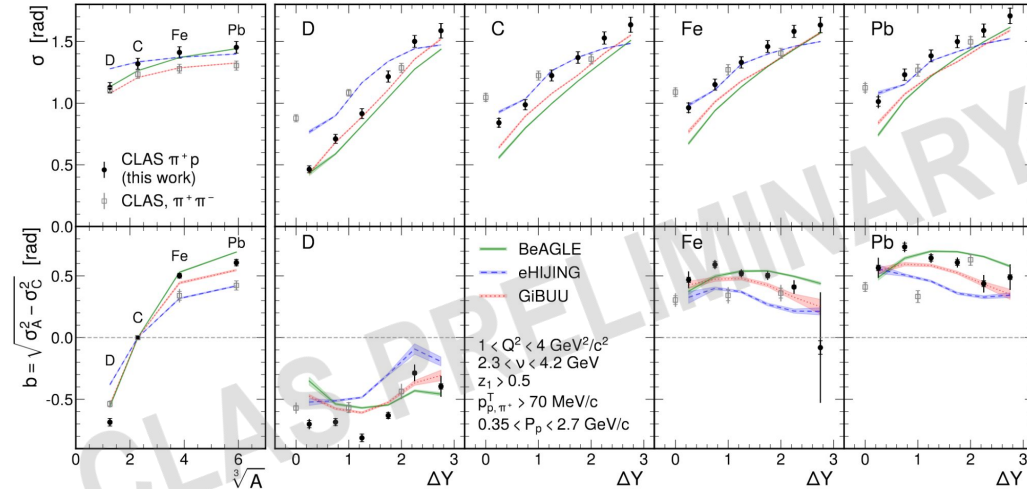
- GiBUU
 - Final-state interactions
 - Absorption
 - Hadron production mechanisms
 - Pre-hadron degrees of freedom
 - Color transparency
 - Nuclear shadowing



Models

- eHIJING

- Based on Pythia8
- Interaction between hadrons and the nuclear medium proportional to the nuclear TMD PDF of gluons.

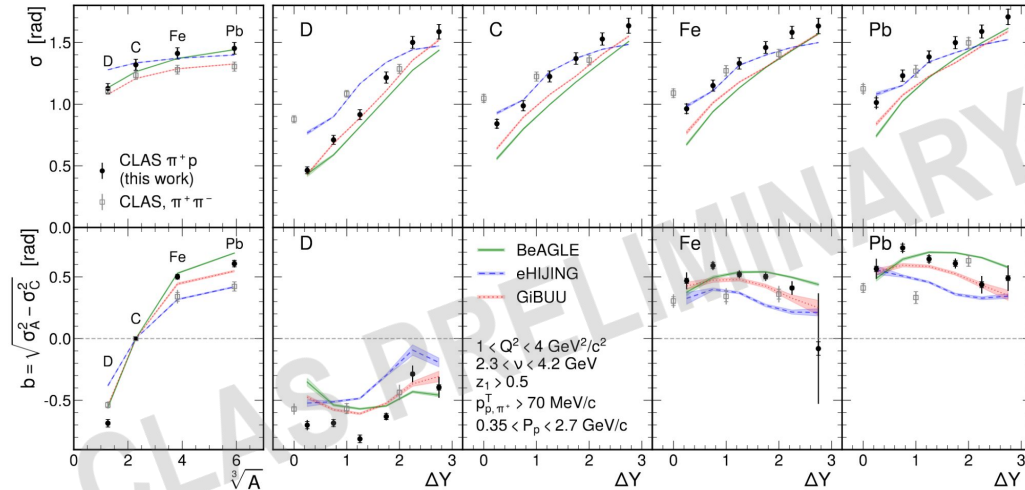


<https://doi.org/10.1103/PhysRevD.10.034001>

Models

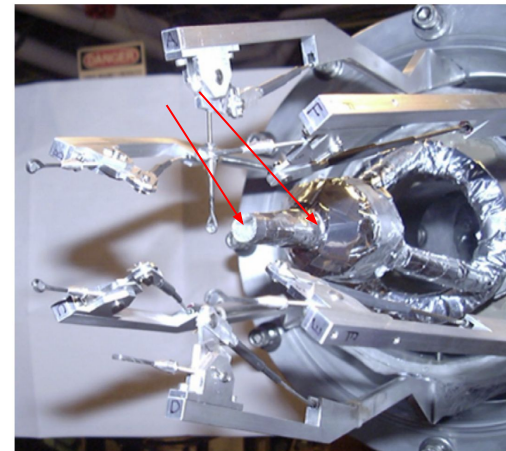
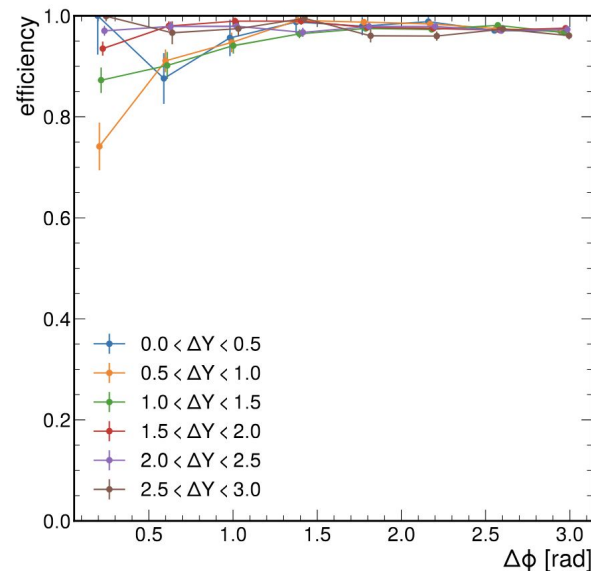
BeAGLE

- 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)



Corrections to correlation functions

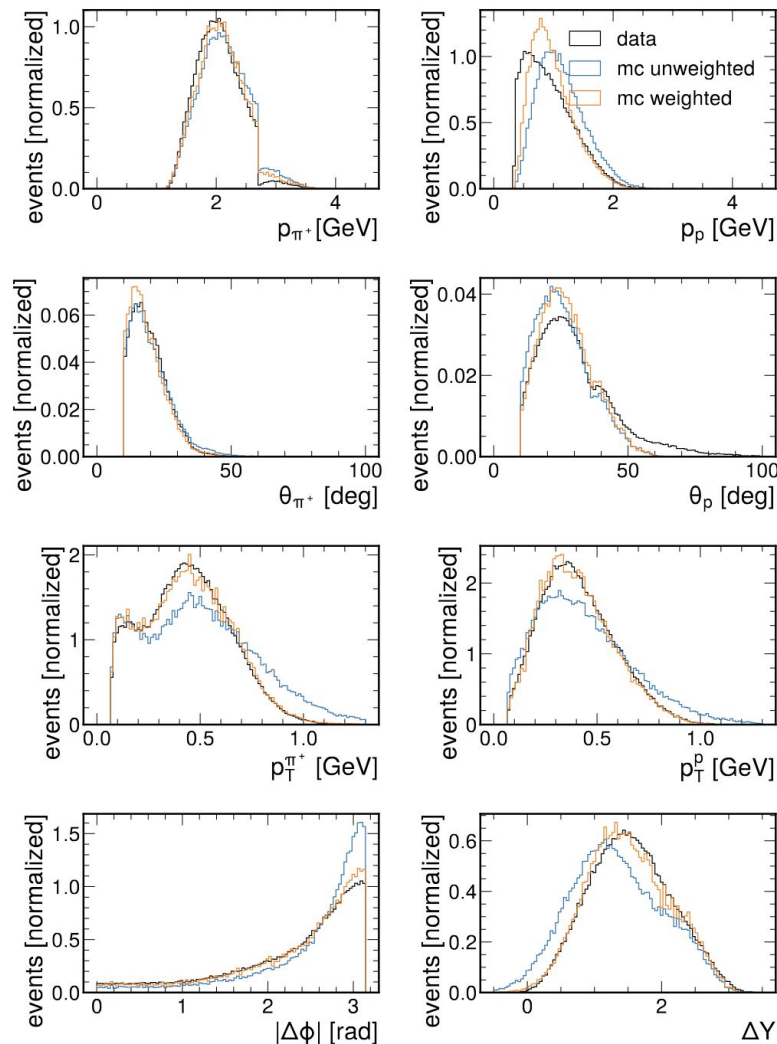
- Acceptance * efficiency determined using MC
 - $$\epsilon_{p,i} = \frac{\sum_{j \in \text{events}} w_j(e'\pi^+ p \text{ detected; in bin } i)}{\sum_{j \in \text{events}} w_j(e'\pi^+ \text{ detected, } p \text{ generated; in bin } i)}.$$
 - Per-event weights determined using OMNIFOLD algorithm*
- Contamination from aluminum endcaps of the deuterium target
 - Determined in a data-driven manner, assuming that the correlation function for aluminum is in between that of C and Fe
- Total corrections were a few percent for most bins



OMNIFOLD

Assigns weights to events using
AI, trained on multiple variables

Improves agreement between data
and Monte-Carlo for distributions of
kinematic variables



Systematic uncertainties (widths/broadenings)

Source	$\Delta\sigma/\sigma$ (D)	$\Delta\sigma/\sigma$ (A)	corr. D vs A	$\Delta b/b$
Statistics	0.4–2%	0.5–4%	N	2–500%
Endcaps	<1%	0%	N	0–3%
Particle misid.	2–3%	2–3%	Y	1–67%
Pair acceptance	2–4%	2–3%	Y	4%
Event selection	1%	1%	Y	0%
Finite bin width	0–3%	0–1%	Y	0–4%
Bin migration	negligible	negligible	–	negligible
Time dependent effects	negligible	negligible	–	negligible
Luminosity	negligible	negligible	–	negligible
Trigger efficiency	negligible	negligible	–	negligible
Syst. subtotal	3–6%	3–4%	Y	4–67%
Total	3–6%	3–6%	Y	4–504%