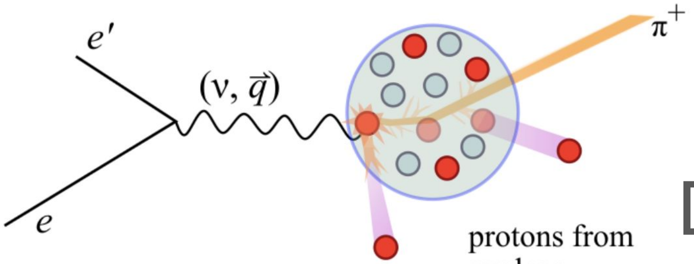
Pion-Proton Correlations in *eA* Scattering



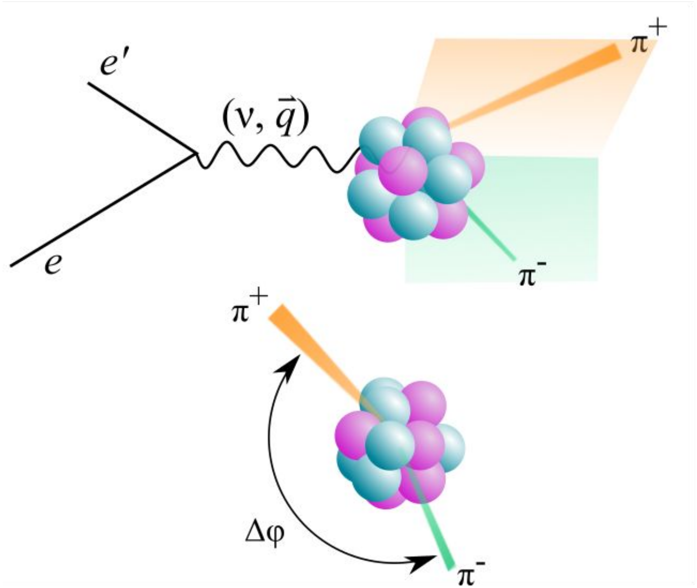
Dr. Sebouh Paul
UC Riverside

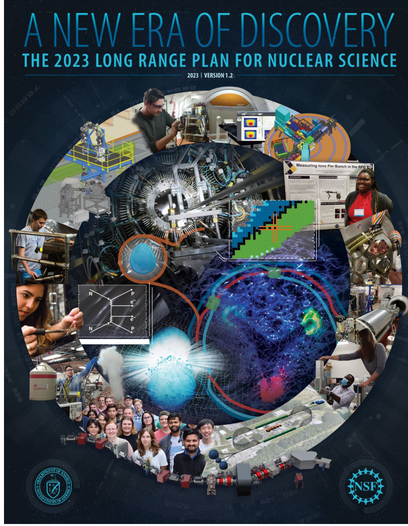
7/11/2025

UC RIVERSIDE

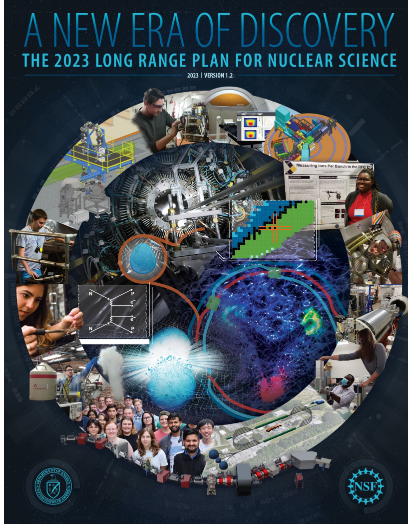
CEBAF Large Acceptance Spectrometer

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

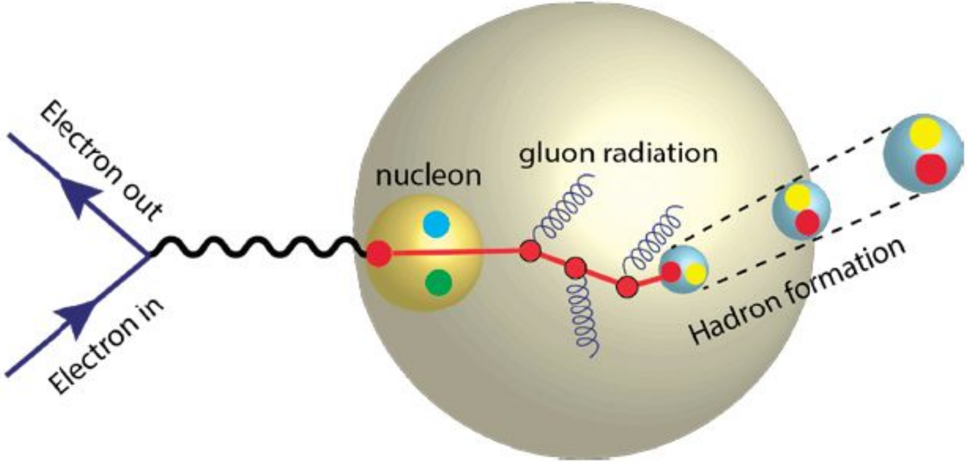




… and how does hadronization change in a dense partonic environment?



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

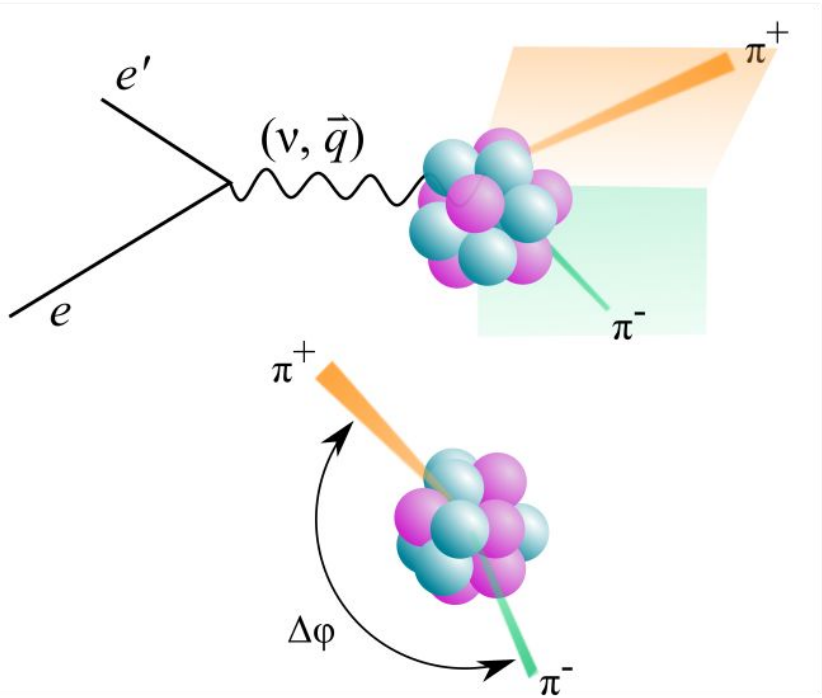


Previous analyses:
di-pion production in nuclei

- Double ratios:
  - Phys. Rev. Lett. 129, 182501 (2022)

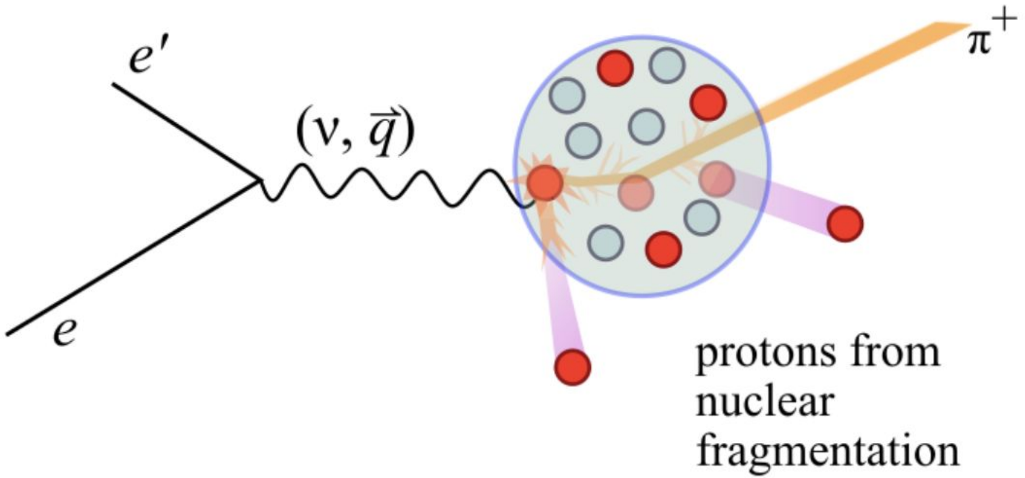
$$R = \frac{((dN_{e'\pi\pi}/dz_2)/N_{e'\pi})^A}{((dN_{e'\pi\pi}/dz_2)/N_{e'\pi})^D}$$

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



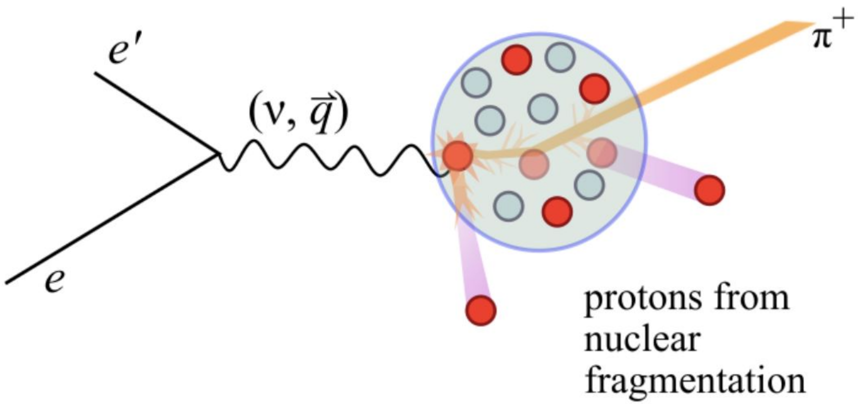
A new event topology: πp

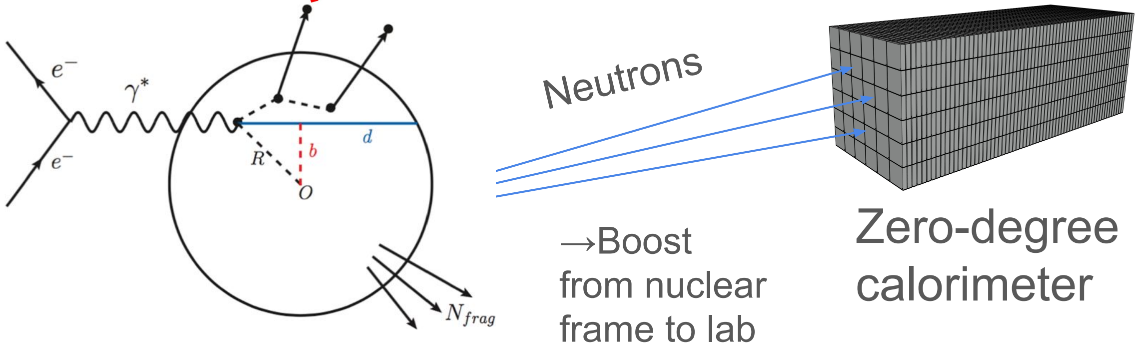
- Electron with DIS kinematics
  - $Q^2 > 1$ GeV^2
  - $W > 2$ GeV
  - $2.3 < \nu < 4.2$ GeV
- High energy π^+
  - $z \equiv E_h/\nu > 0.5$
- A secondary proton
  - Originates from the fragmentation of the nucleus



“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.



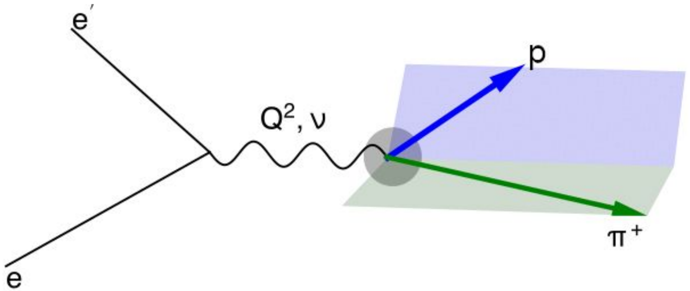


→Boost from nuclear frame to lab frame

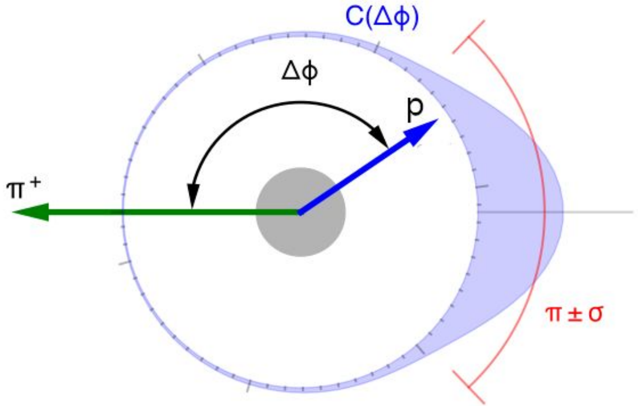
*Phys. Rev. C **106**, 045202, Phys. Rev. C **101**, 014617

Correlation function

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

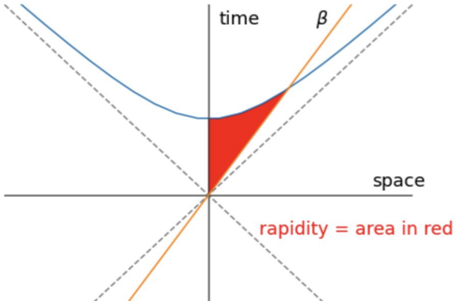


$$C(\Delta\phi, \Delta Y) \equiv C_0 \times \frac{1}{N_{e'\pi}} \frac{dN_{e'\pi p}}{d\Delta\phi \; d\Delta Y}$$



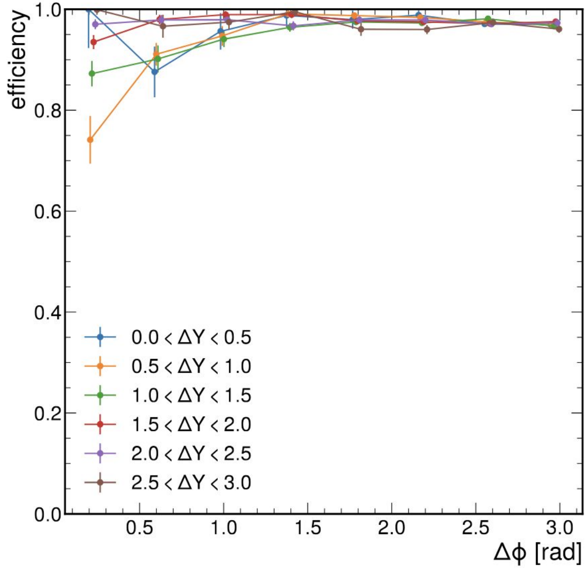
$$\Delta Y = Y_{\pi^+} - Y_p$$

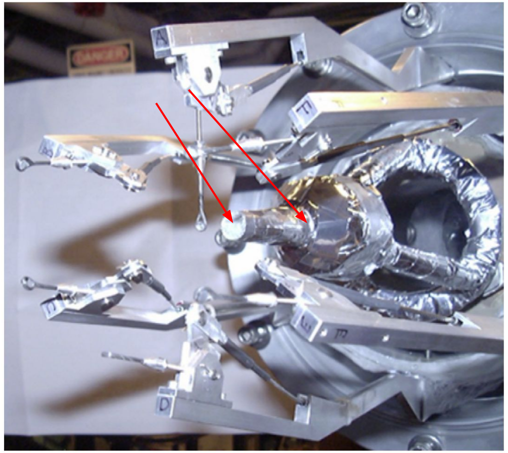
$$Y = \frac{1}{2}\log\frac{E + p_z}{E - p_z}$$



Corrections to correlation functions

- Acceptance * efficiency determined using MC
  - $$\epsilon_{p,i} = \frac{\sum\limits_{j \in events} w_j(e'\pi^+ p \,\text{detected; in bin}\, i)}{\sum\limits_{j \in events} w_j(e'\pi^+ \,\text{detected}, p \,\text{generated; in bin}\, i)}.$$
  - 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





*Phys. Rev. Lett. 124, 182001

Systematic uncertainties

- Determined bin-by-bin.
- Median syst. uncertainty: ~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%

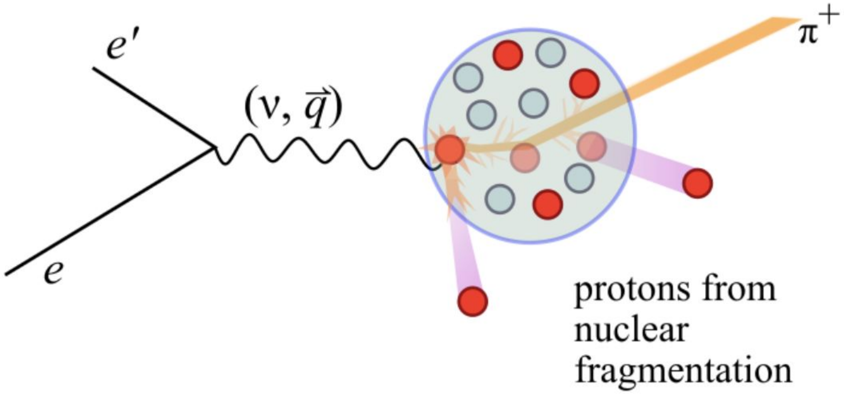
Review status

Analysis review completed 6/6/2025

Ad-hoc review (first round) began 7/9/2025

Pending ad-hoc and collaboration-wide review…

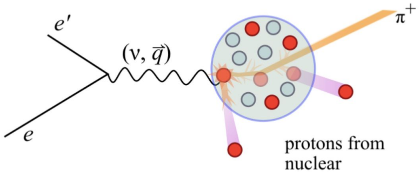
to be sent to PRL for publication

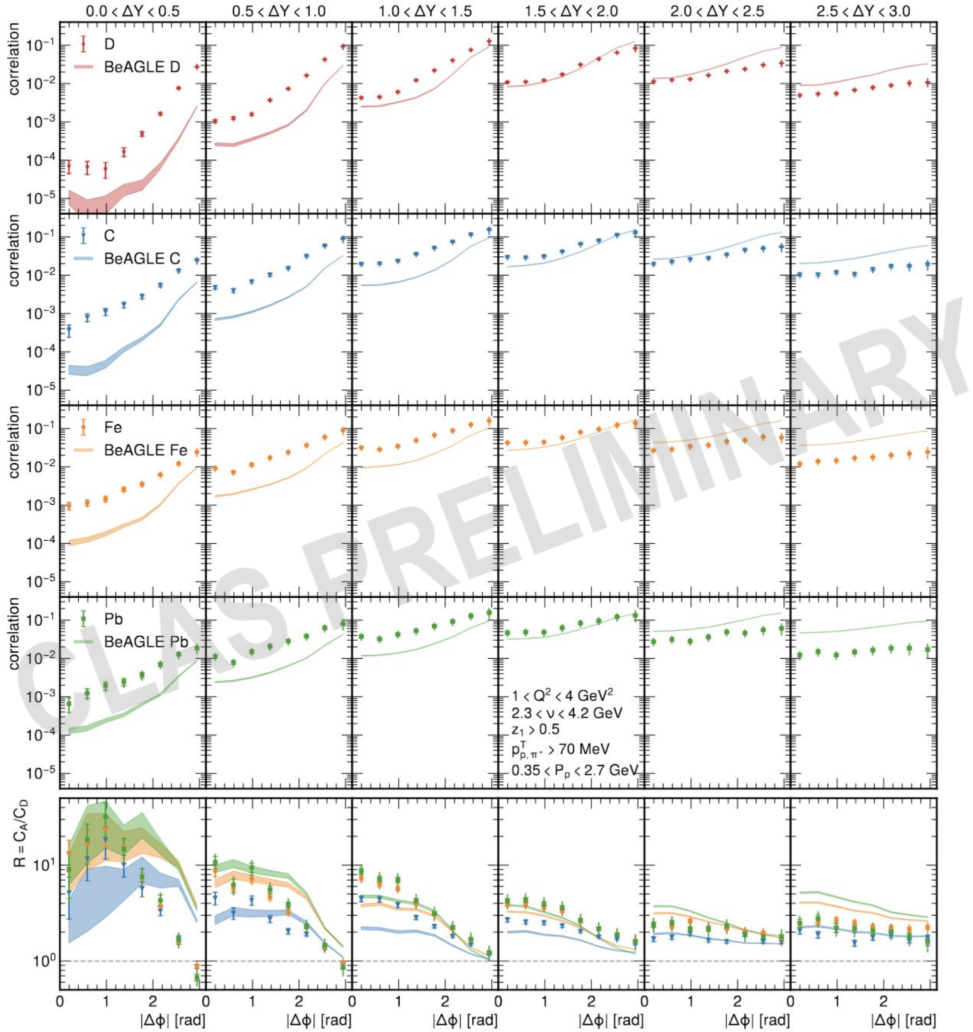


Measured correlation functions

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

- Peaks at Δφ≈π, 1.0<ΔY<1.5

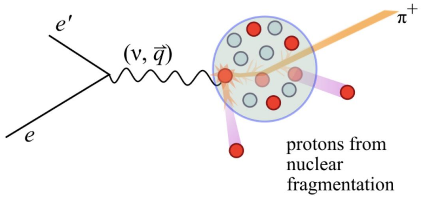


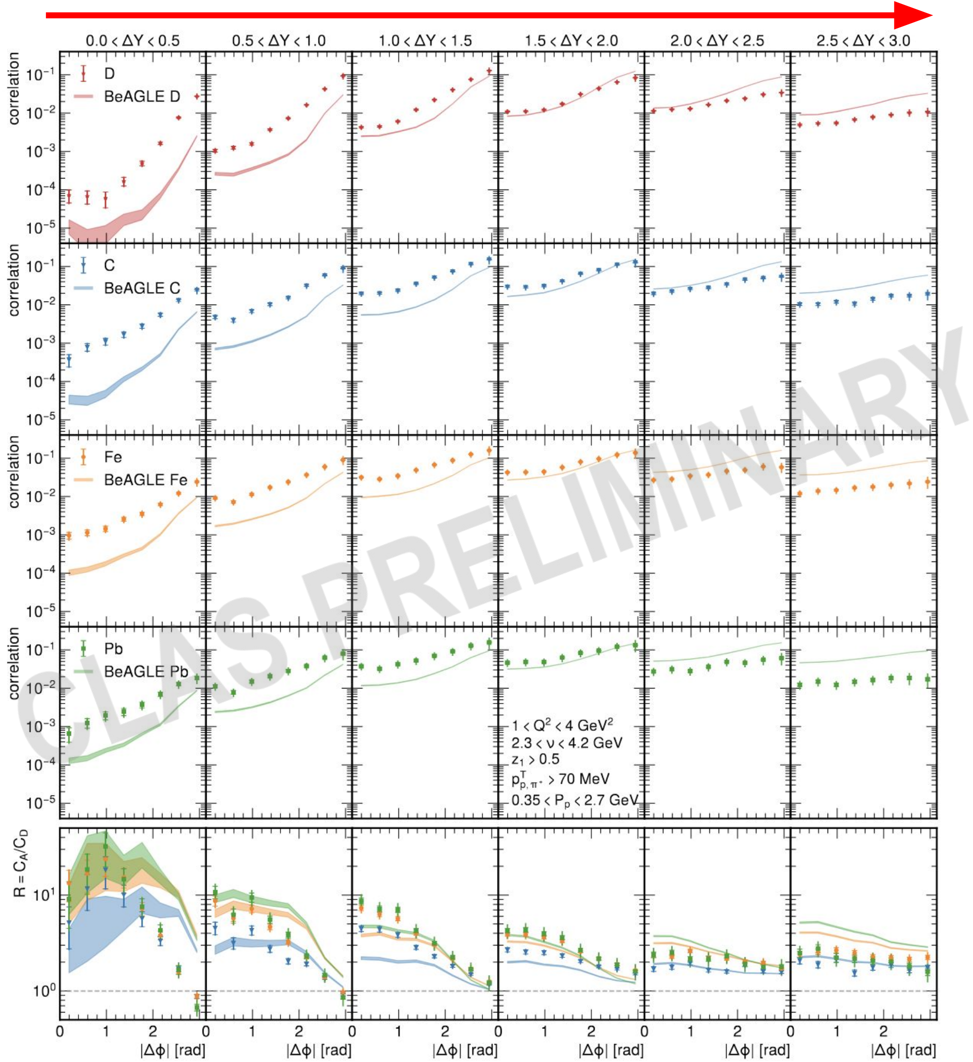


Measured correlation functions

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

- Correlation function has wider peak at larger ΔY

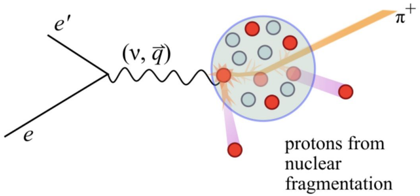


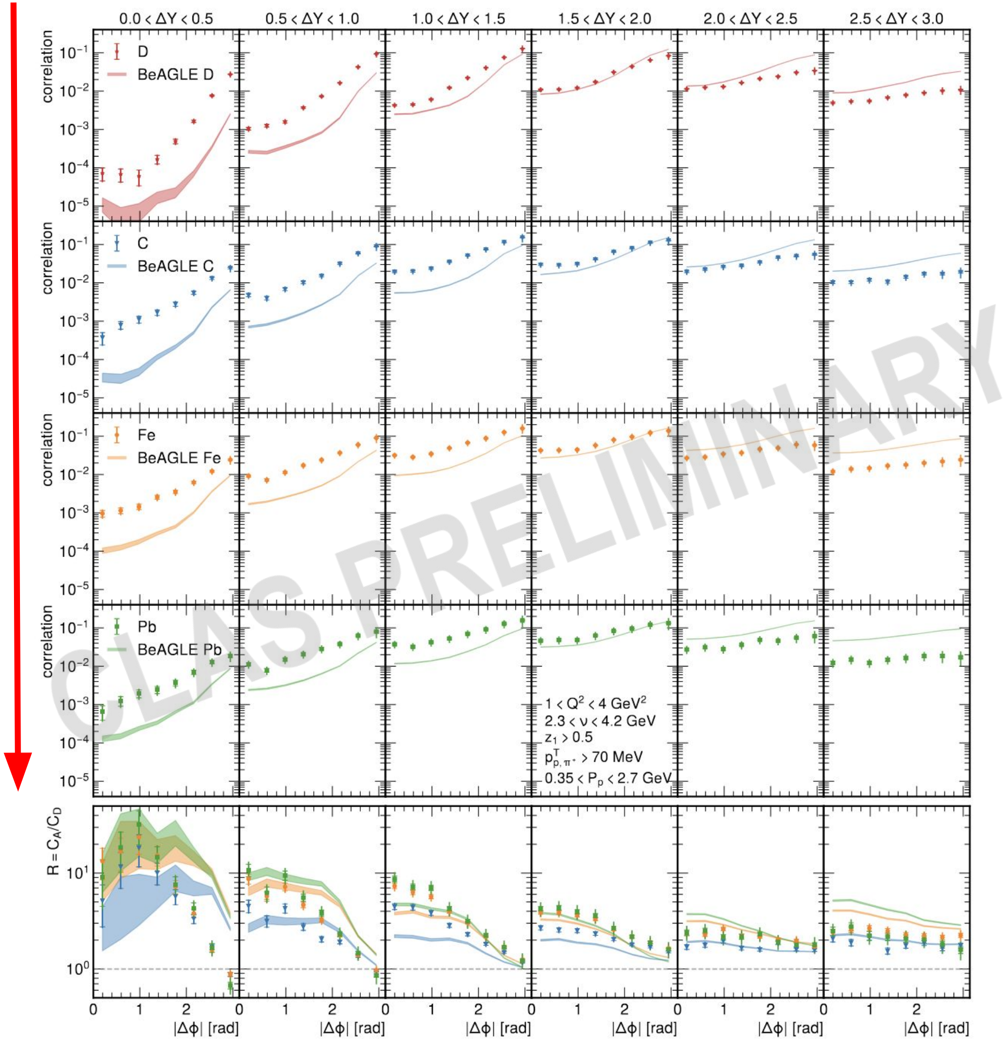


Measured correlation functions

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

- Also, wider peak for heavier targets

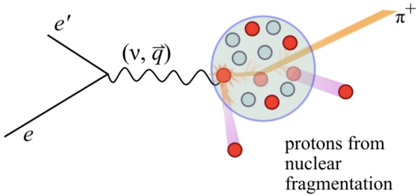


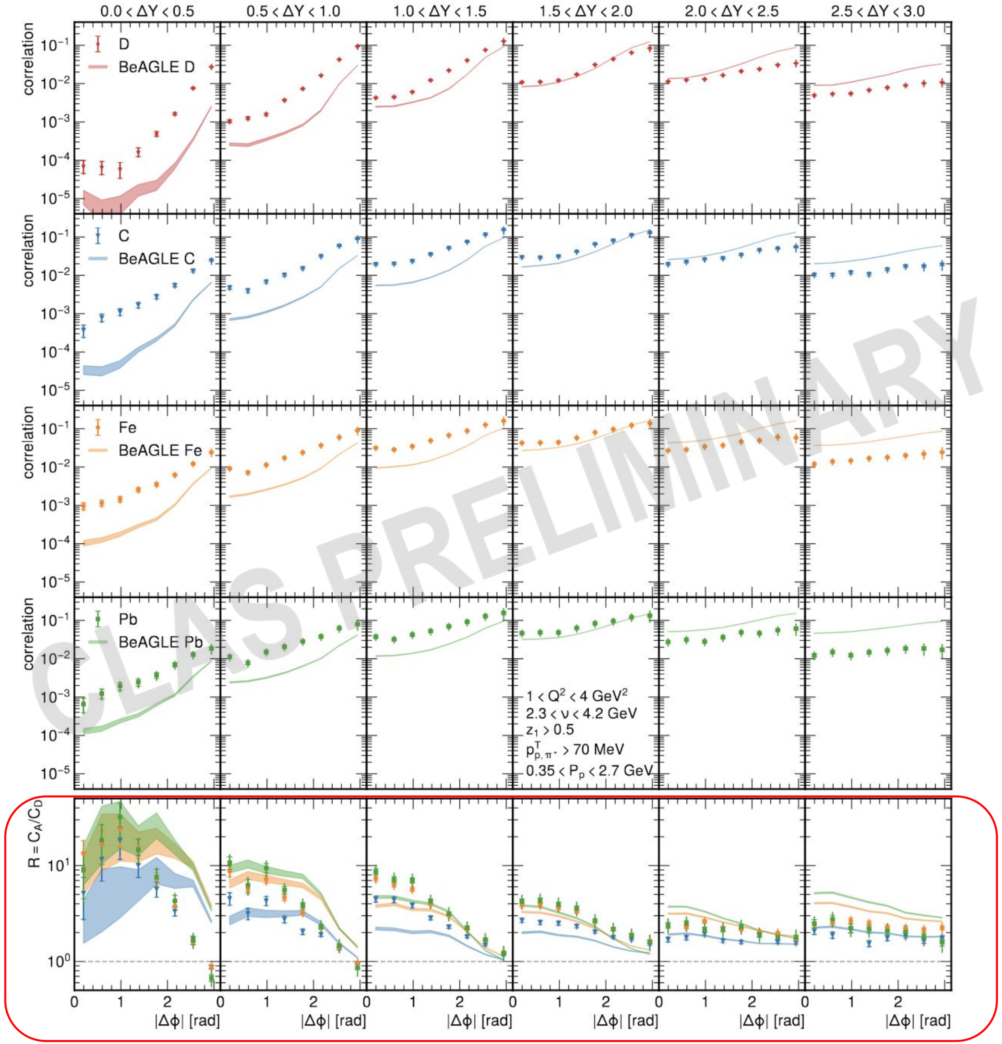


Measured correlation functions

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

- A/D ratio is >1 for most bins, more protons per pion in heavier nuclei, though this appears to saturate



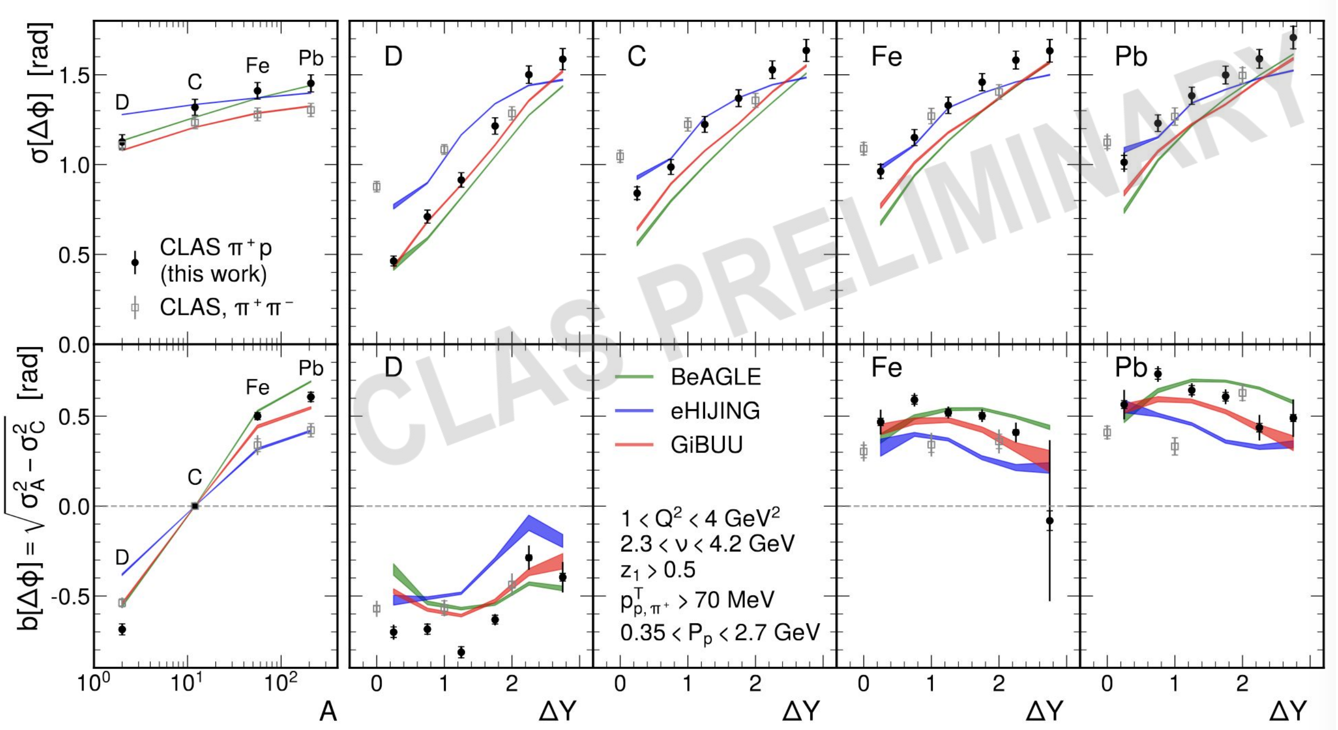


RMS widths and broadenings

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

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

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

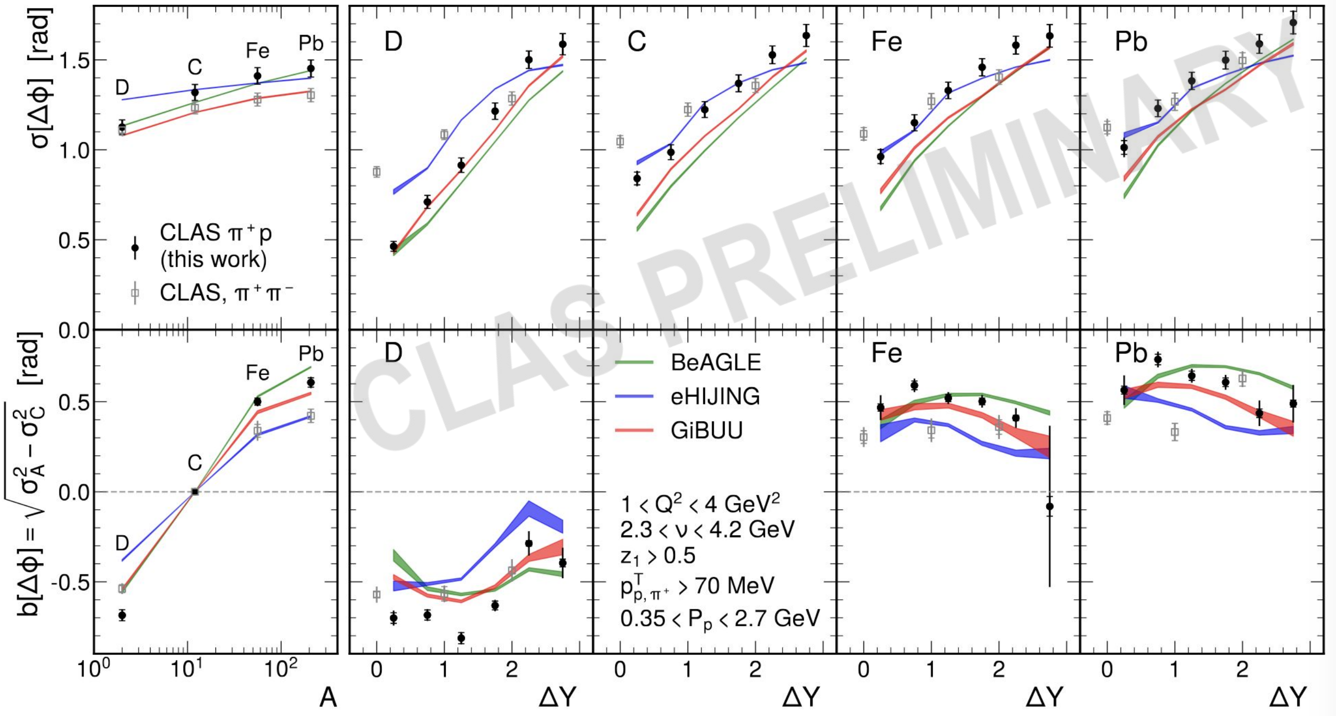


RMS widths and broadenings

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

- 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

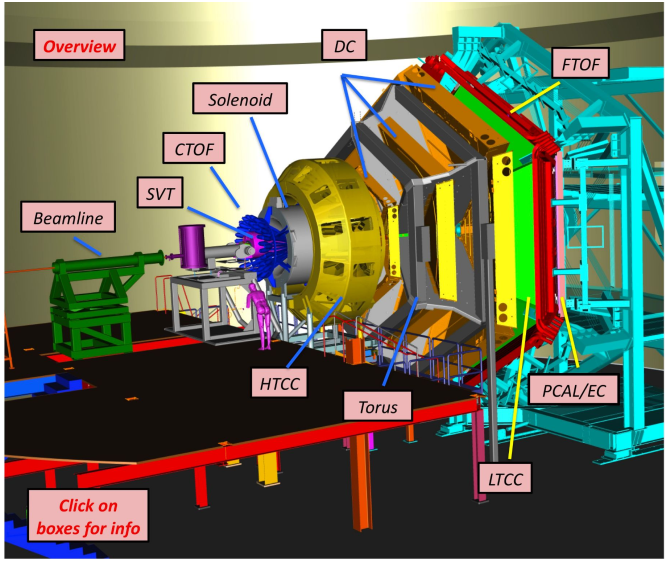
$$b = \pm\sqrt{\sigma_A^2 - \sigma_C^2}$$



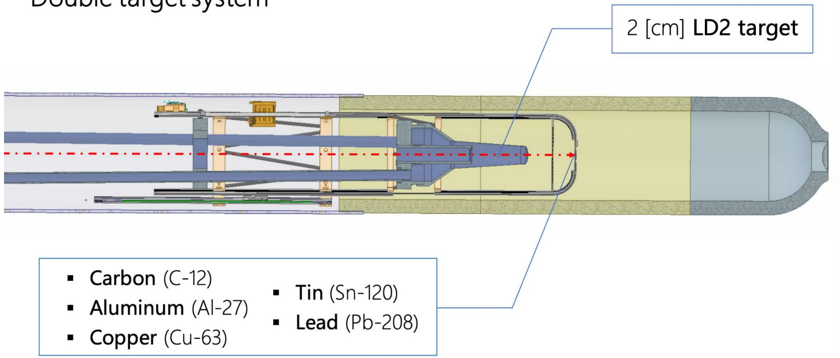
Follow-up measurements with upgraded CLAS12 (Run Group E)

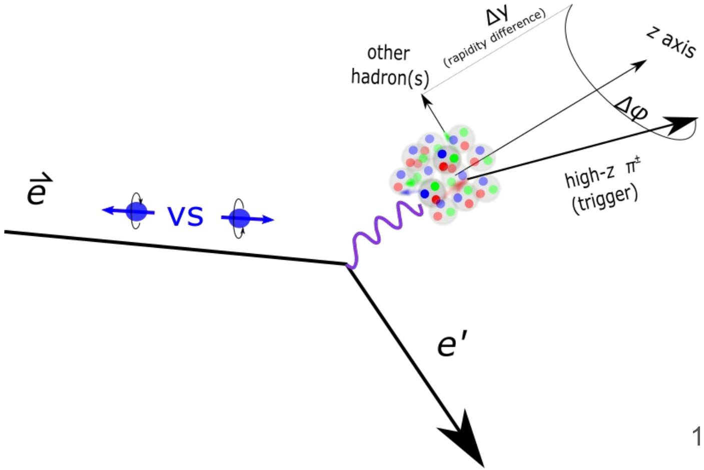
These di-hadron measurements can be extended using recent measurements with

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



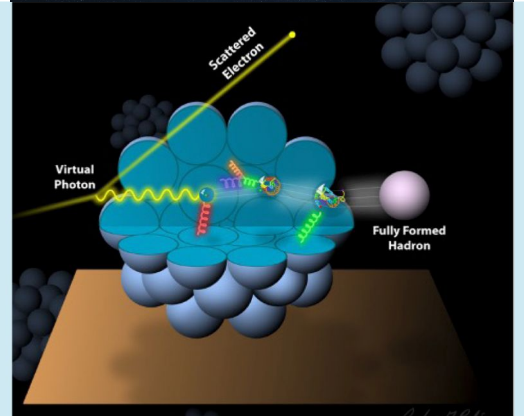
Double target system





Summary

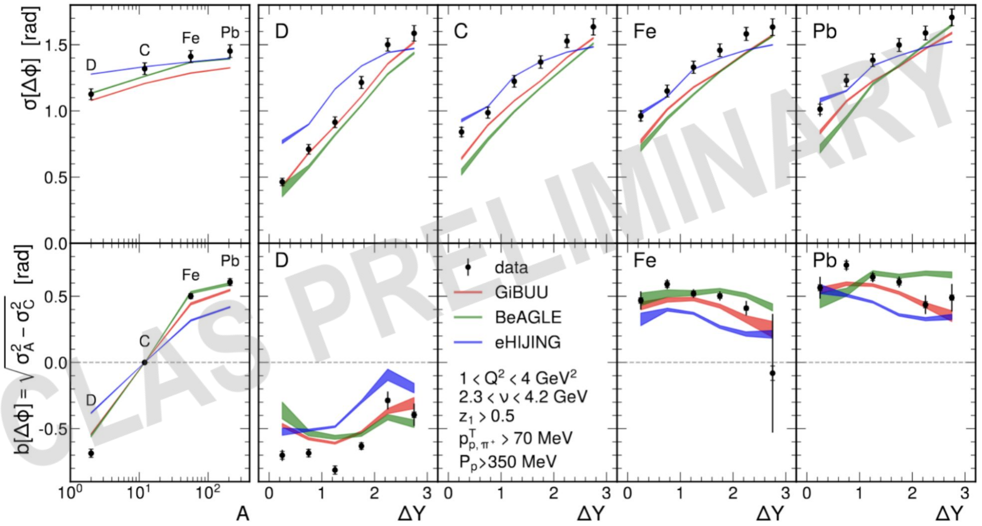
- Di-hadron correlations represents a new tool to explore how hadronization is affected by nuclei
- Current and future analyzes with RGE will seek to answer some of the questions raised in the 2023 LRP
    - How are the various hadrons produced in a single scattering process correlated with one another 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 ππ channel.
- πp correlation analysis has just started ad-hoc review.



Backup slides

Models

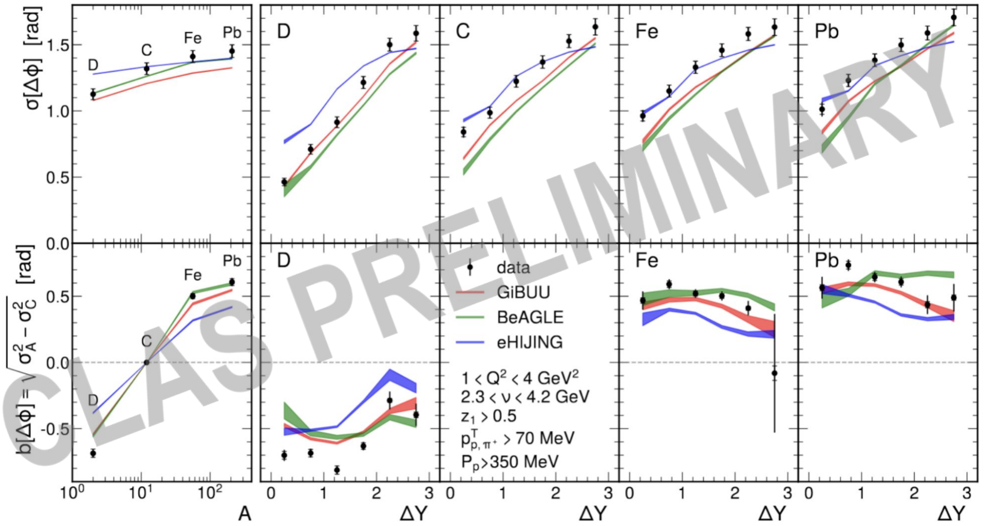
- GiBUU
  - Final-state interactions
  - Absorption
  - Hadron production mechanisms
  - Pre-hadron degrees of freedom
  - Color transparency
  - Nuclear shadowing



https://doi.org/10.1016/j.physrep.2011.12.001

Models

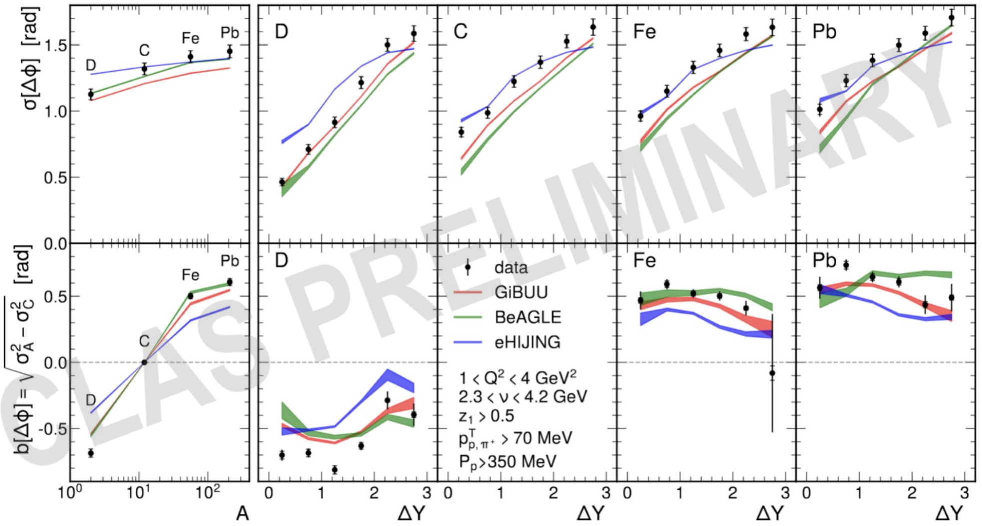
- eHIJING
  - Based on Pythia8
  - Interaction between hadrons and the nuclear medium proportional to the nuclear TMD PDF of gluons.



https://doi.org/10.1103/PhysRevD.110.034001

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)

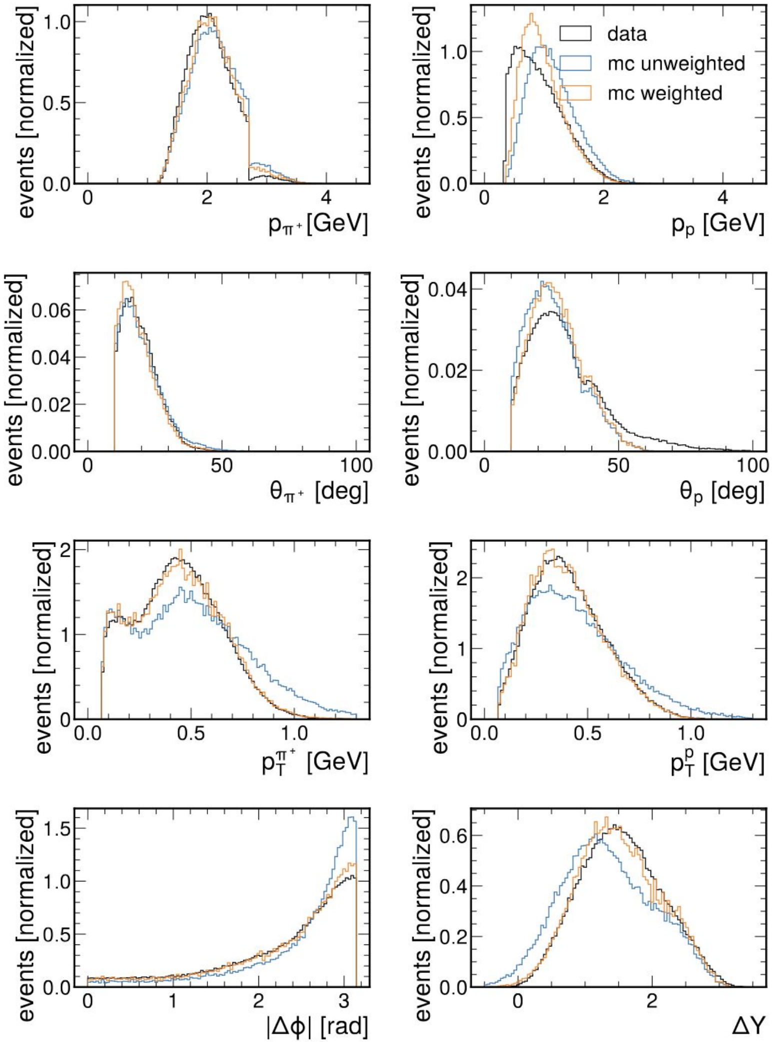


https://doi.org/10.1103/PhysRevD.106.012007

OMNIFOLD

Assigns weights to events using AI, trained on multiple variables

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



Phys. Rev. Lett. 124, 182001

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%