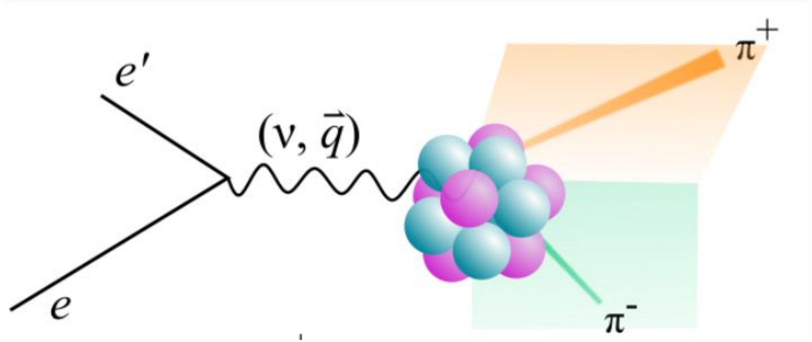
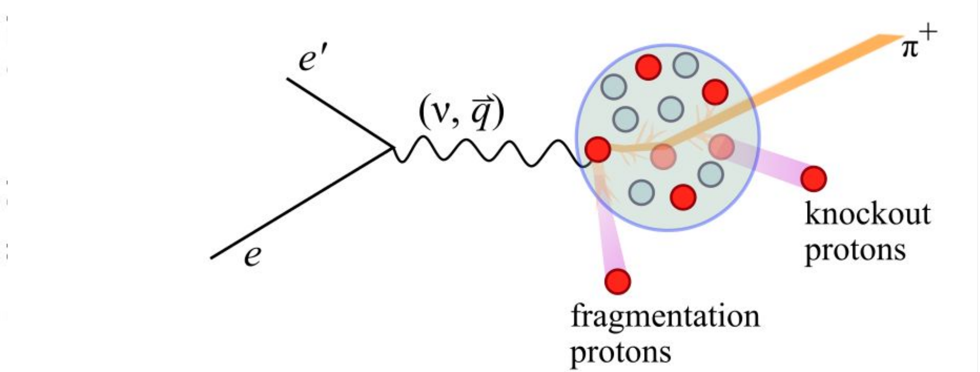
Di-hadron Correlations in eA Scattering in CLAS





Ryan Milton on behalf of Dr. Sebouh Paul

GHP2025

3/14/2025

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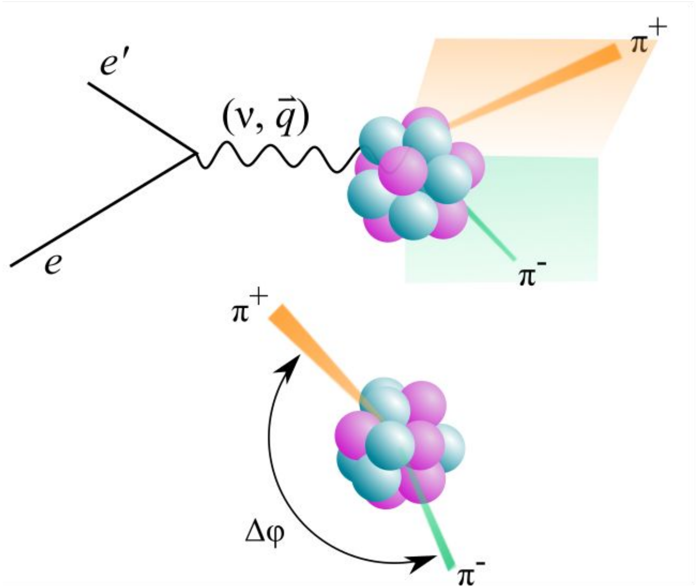
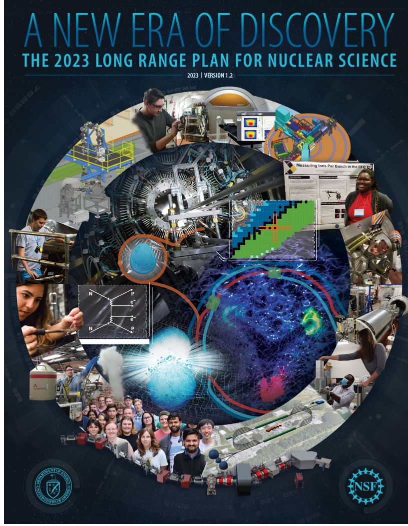
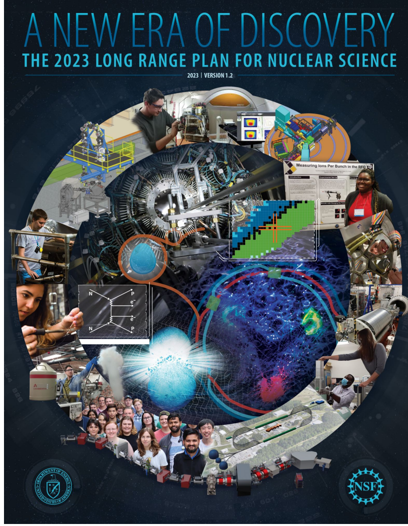
APS Topical Group on Hadronic Physics GHP

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

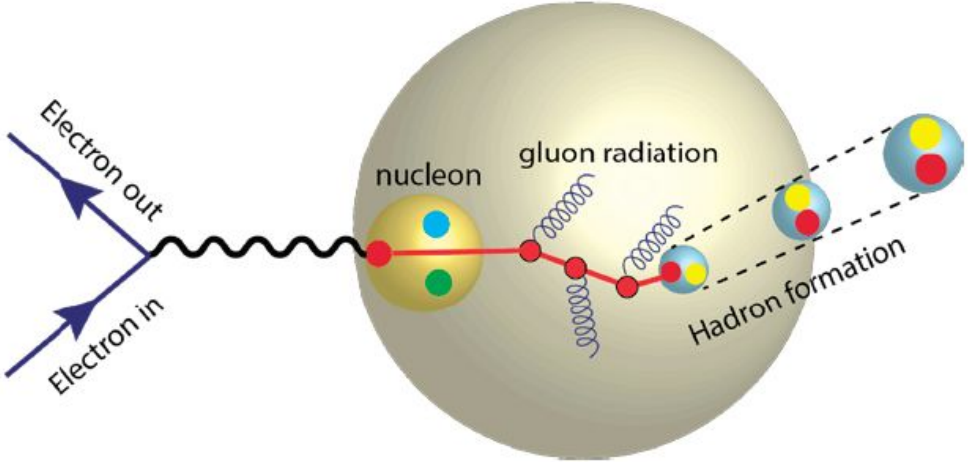




… and how does hadronization change in a dense partonic environment?

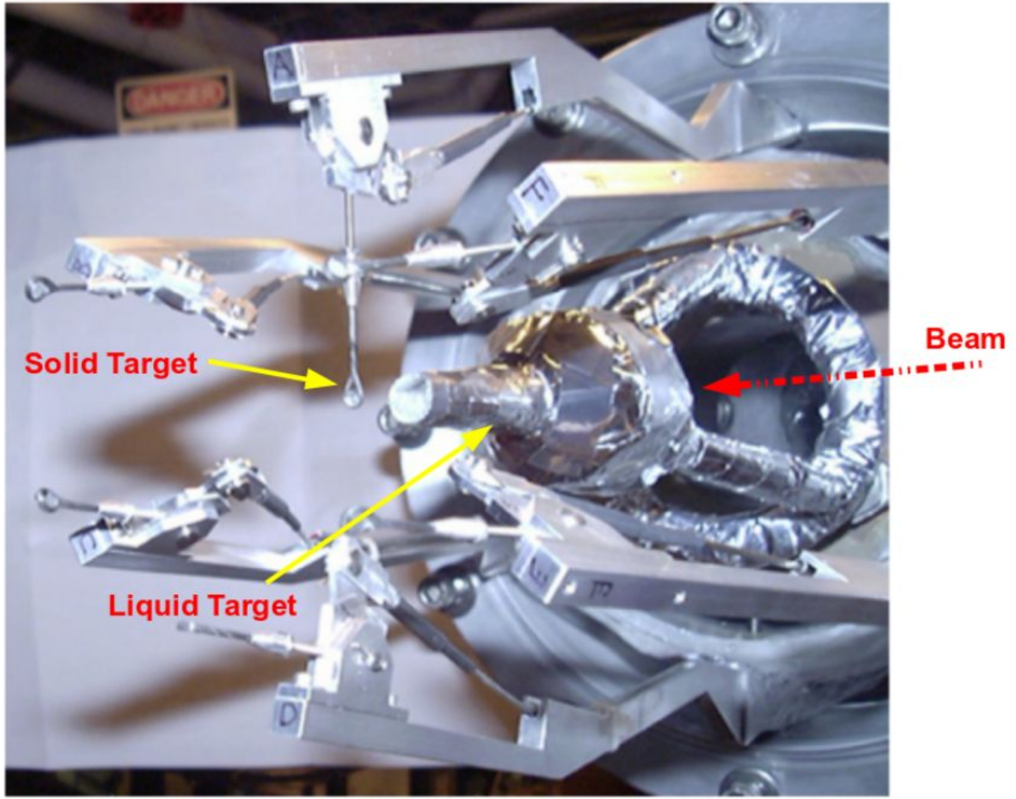


And what are the timescales of color neutralization and hadron formation?



CLAS EG2 experiment

- 5 GeV electron beam
- Liquid (LD2) + Solid dual target system
  - Solids: C, Al, Pb, Fe, Sn



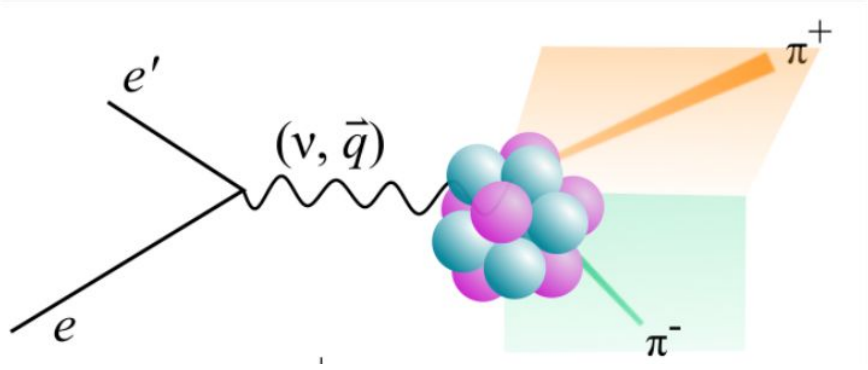
Event topologies

Di-pion:

- High energy π+ and low energy π-

https://doi.org/10.1103/PhysRevLett.129.182501 Phys. Rev. Lett. 129, 182501

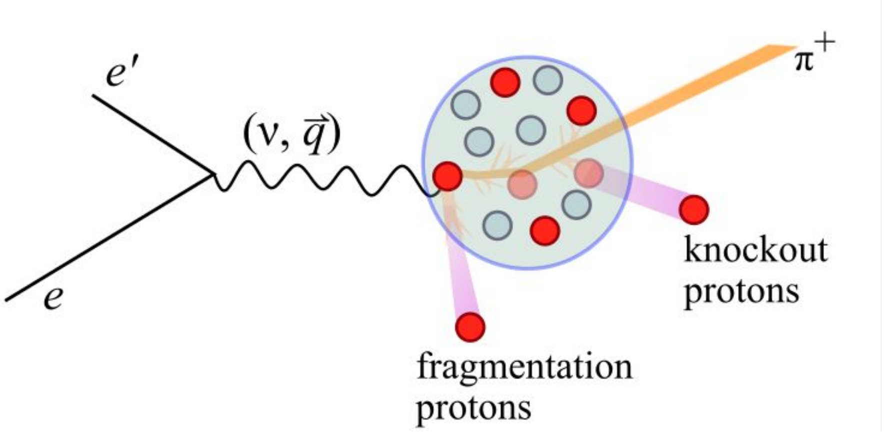
https://doi.org/10.1103/PhysRevC.111.035201, Phys. Rev. C **111**, 035201



Pion+proton

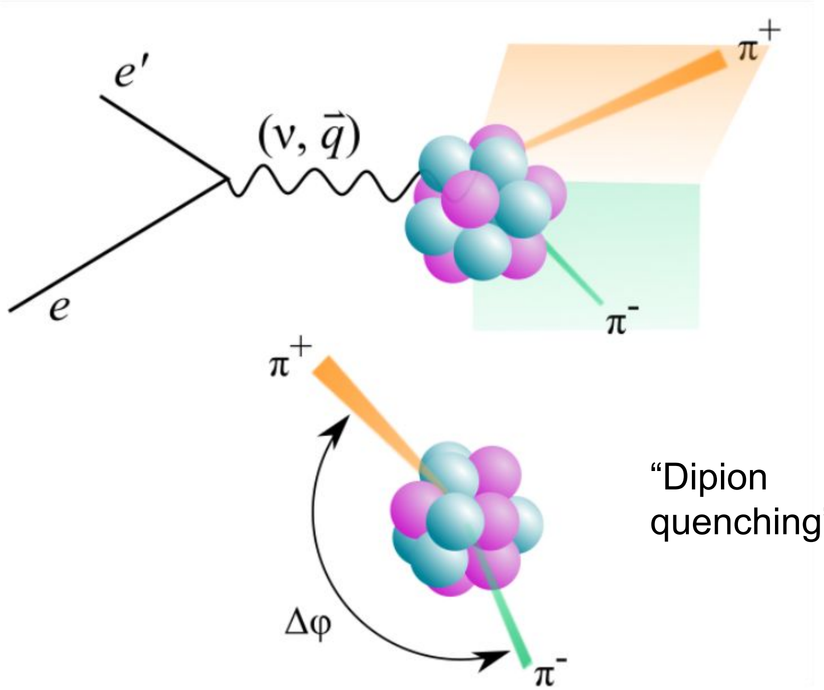
- High energy π+ and knocked-out proton (or proton from fragmentation)

Analysis note in second round of review

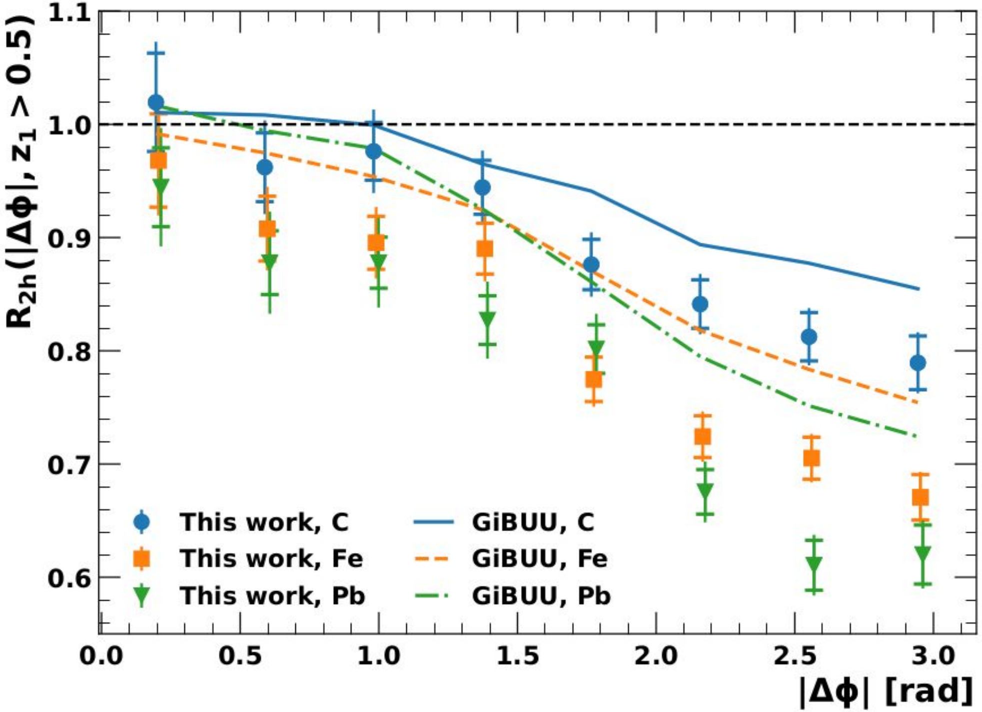


Earlier results …

Discovery of back-to-back pion suppression in eA scattering



"Dipion quenching"



https://doi.org/10.1103/PhysRevLett.129.182501 Phys. Rev. Lett. 129, 182501

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

Our observable: correlation function

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

- 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

Dihadron azimuthal correlations in deep-inelastic scattering off nuclear targets

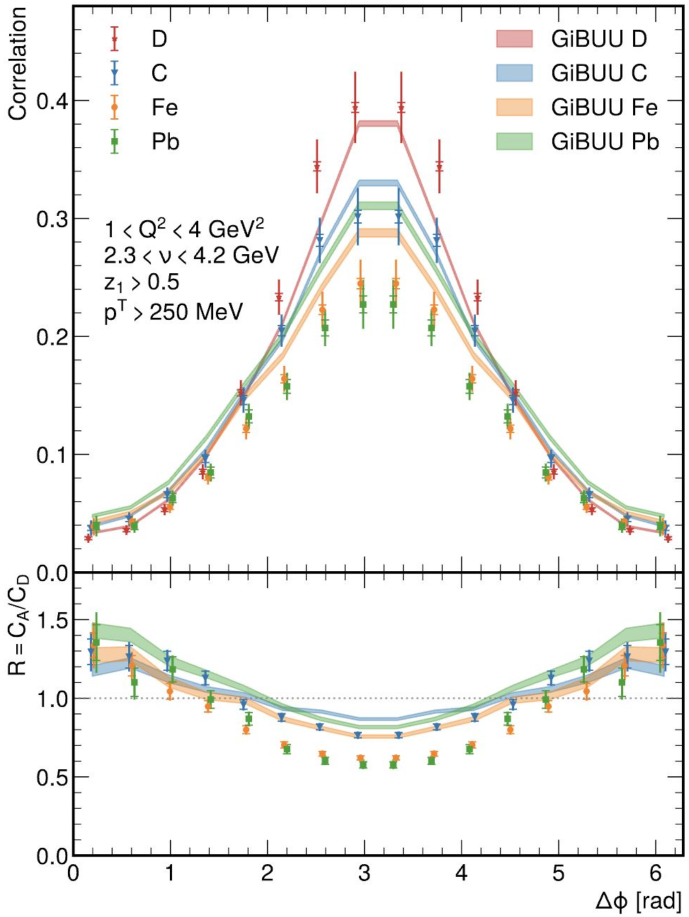
S. J. Paul[4], S. Morán[4], M. Arratia[4,*], W. K. Brooks[43,42], H. Hakobyan[43], A. El Alaoui[43], P. Achenbach[42], J. S. Alvarado[24], W. R. Armstrong[1] *et al.* (CLAS Collaboration)

Show more

Phys. Rev. C **111**, 035201 – **Published 5 March, 2025**

DOI: https://doi.org/10.1103/PhysRevC.111.035201

Leading π^+, subleading π^-

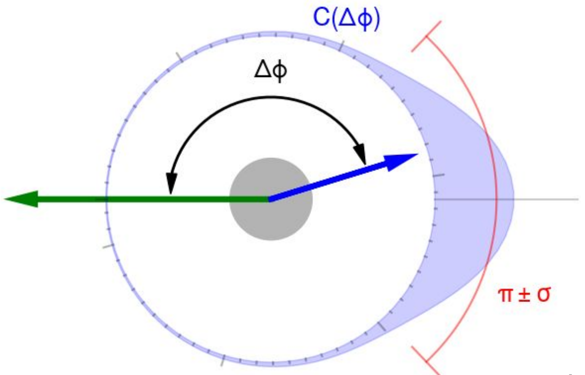


Derived quantities: RMS widths and broadenings

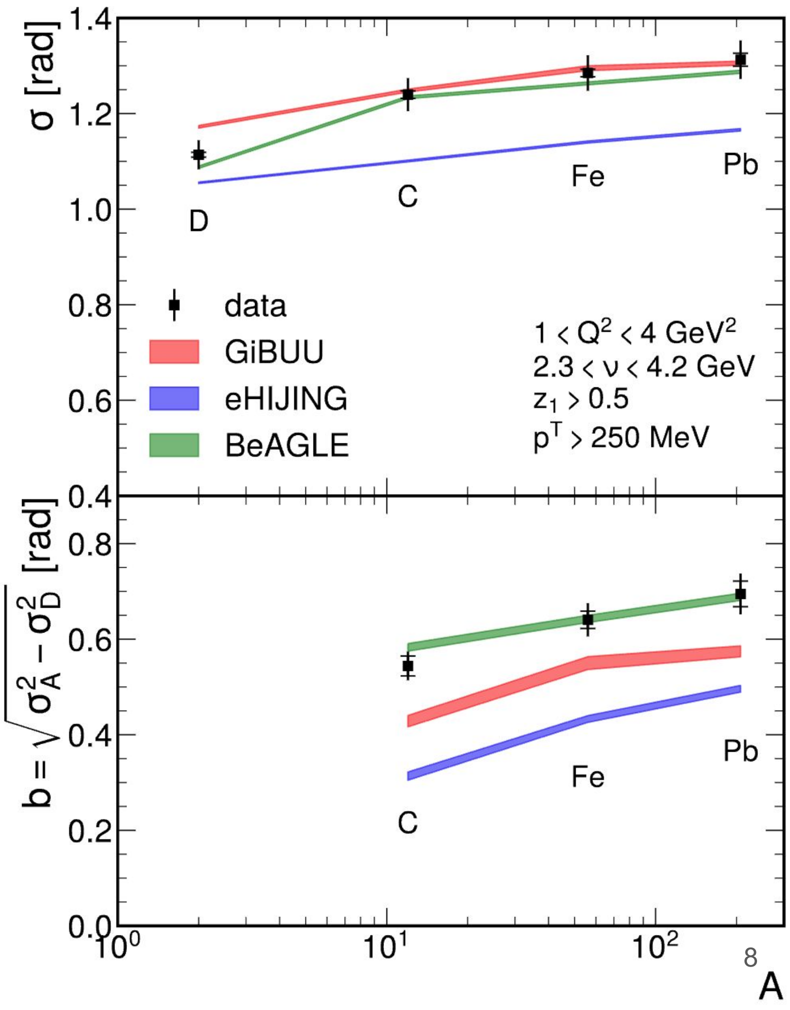
RMS width:

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

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

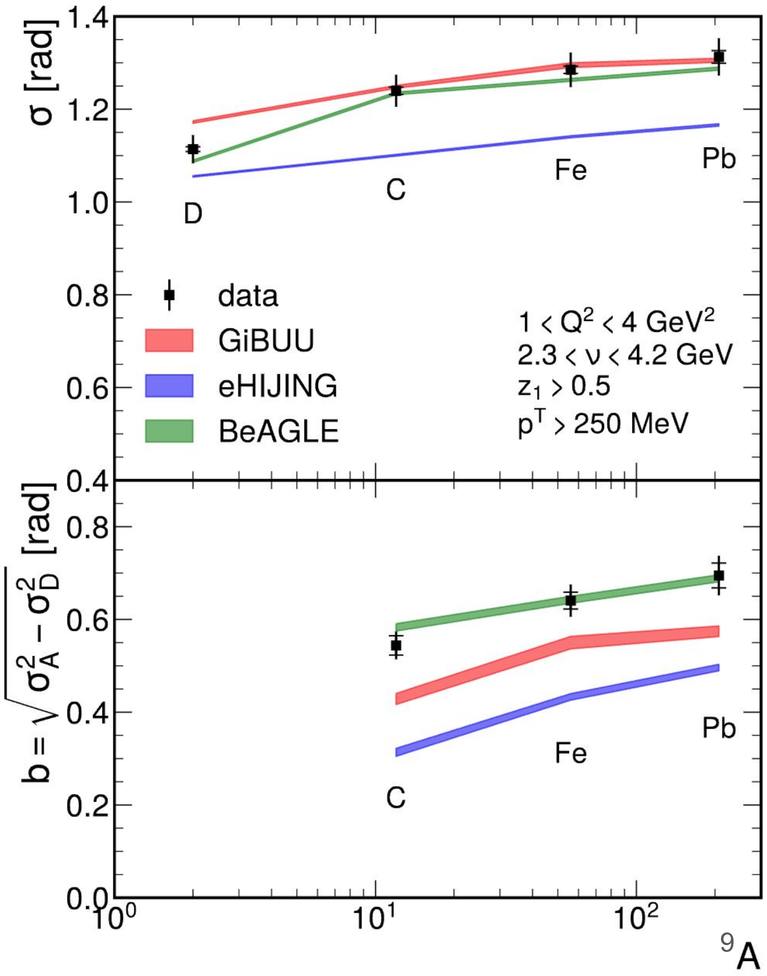


Leading π^+, subleading π^-



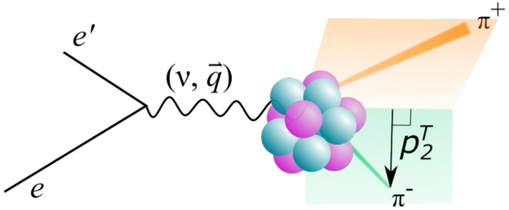
Derived quantities: RMS widths and broadenings

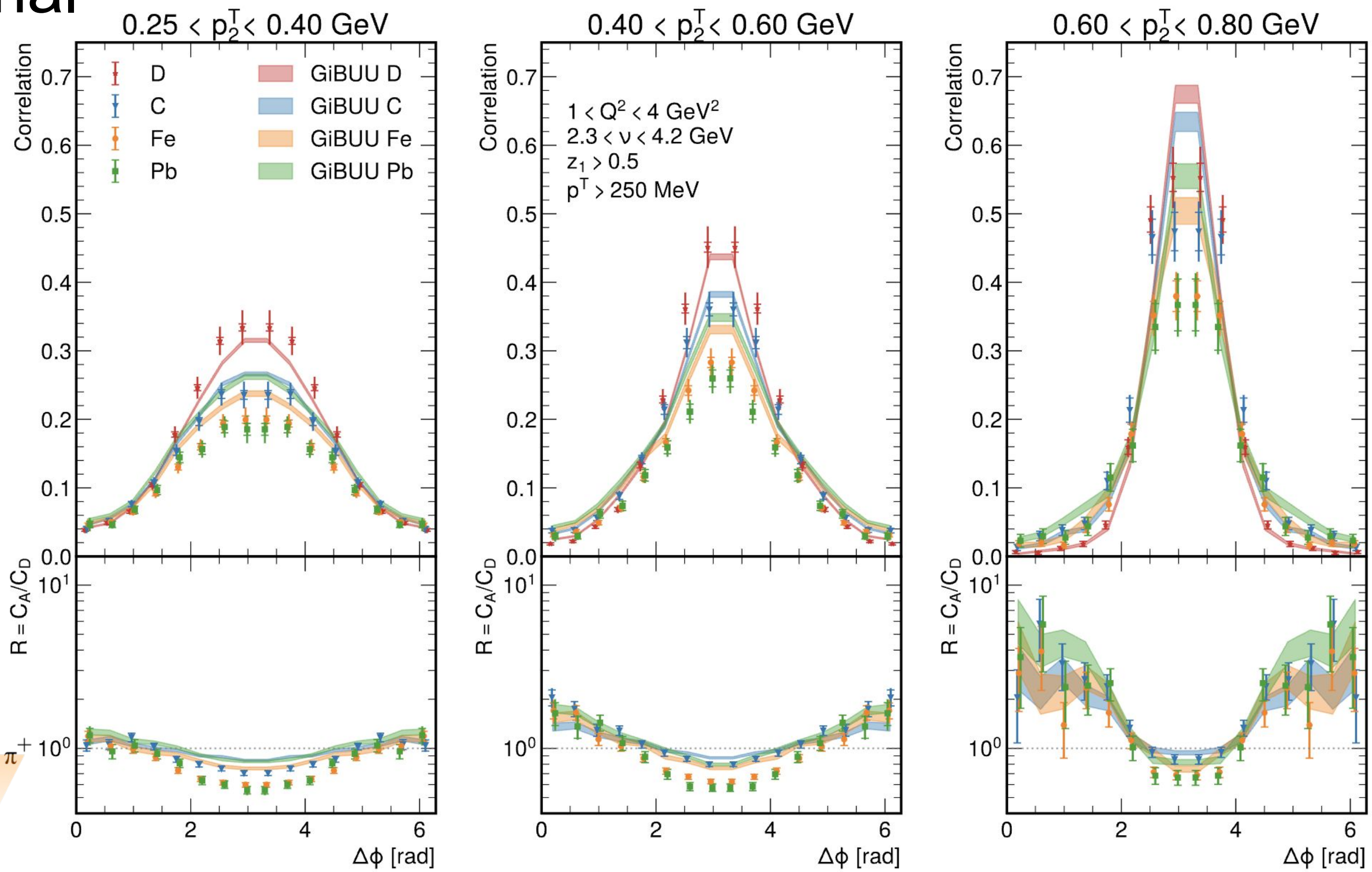
- RMS widths and broadening increase with larger nuclei with weak, log-like A dependence.
- Most of these models are new, developed for the EIC rather than JLab energies, yet predict this trend correctly



Multi-dimensional measurements

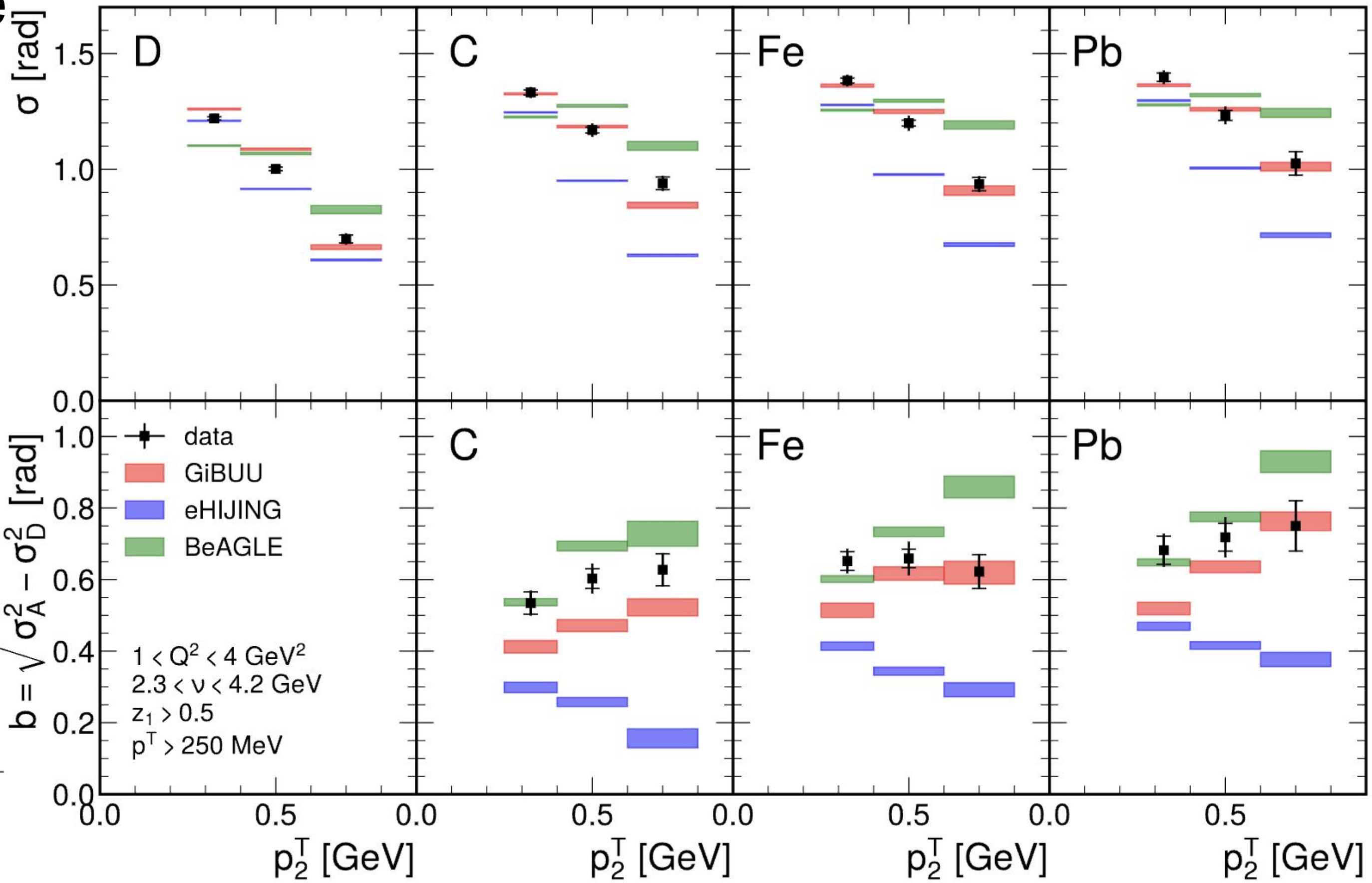
- At large p^T_2, the correlation function peak becomes more narrow
- Nuclear effects strongly depend on p^T_2

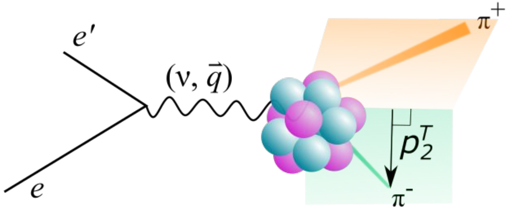




p_2^T dependence

- Models predict different trends in the broadening vs p_2^T, which demonstrates the discriminating power of these measurements



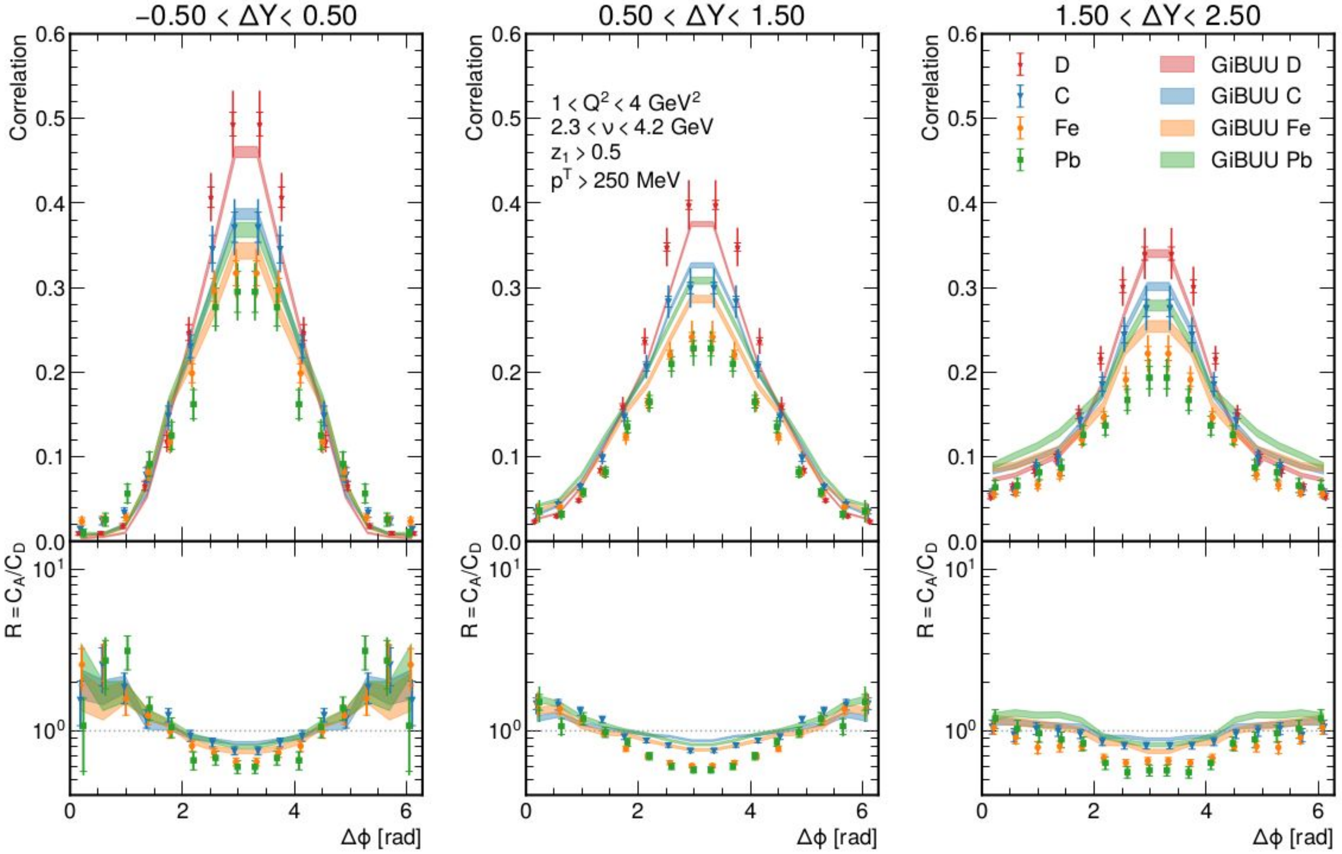


Multi-dimensional measurements

- See opposite trend with ΔY
- Pions with high-rapdity are less correlated than those with lower ΔY

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

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

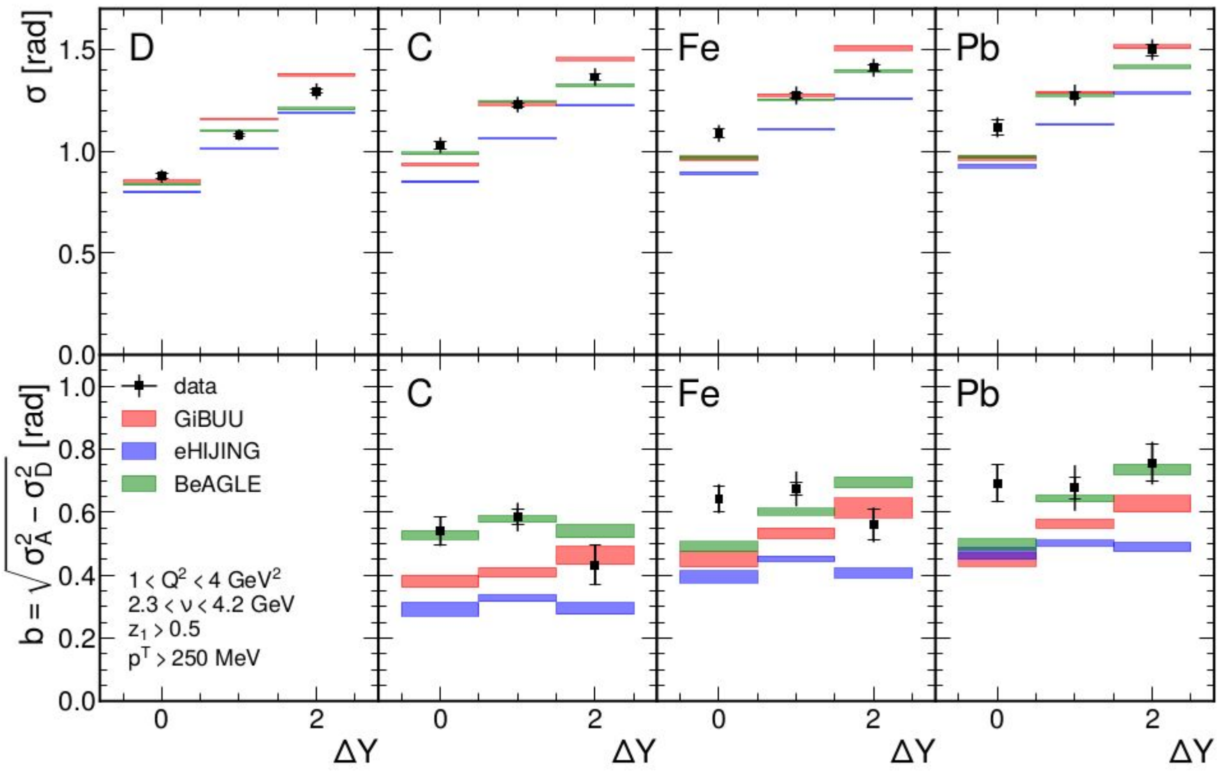


ΔY dependence

- Models predict different trends in the broadening vs ΔY

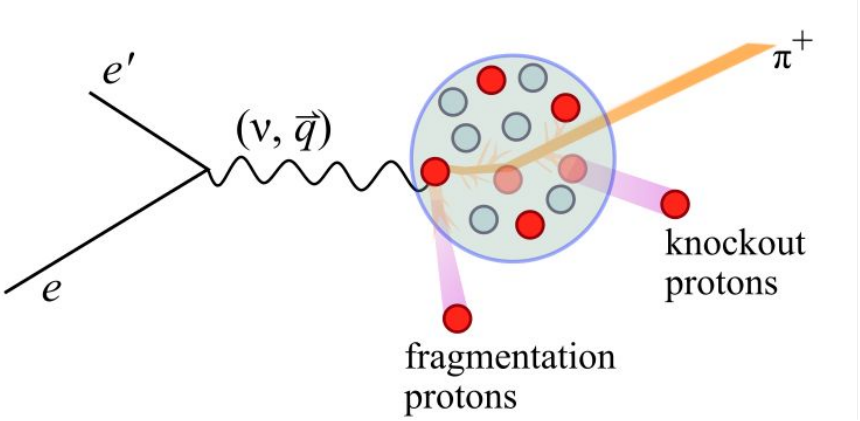
$$\Delta Y = Y_{\pi^+} - Y_p$$

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

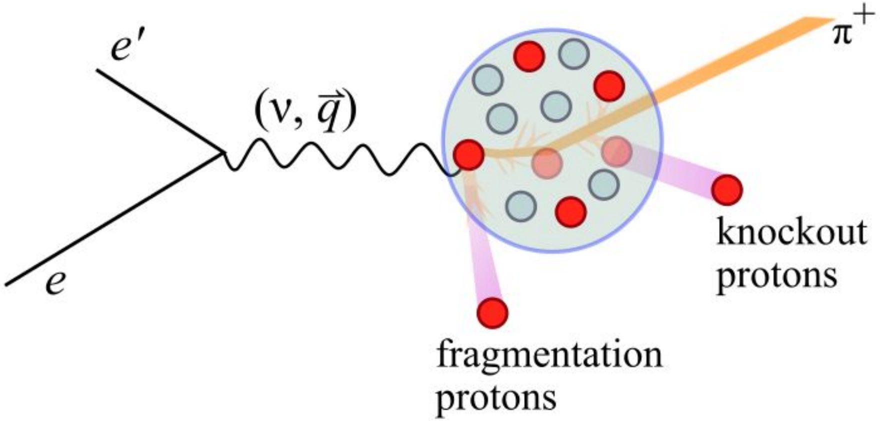


How does the nucleus react to a fast quark?

Protons proxy for "nuclear response"



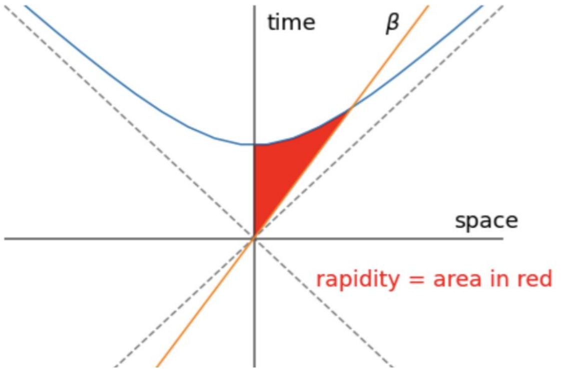
Pion-proton analysis



- Leading π+ and a proton
- Two means of proton production:
  - Knockout (requires much less energy than secondary pion production)
  - Fragmentation of struck nucleon
- Correlation function differential in Δφ and ΔY

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

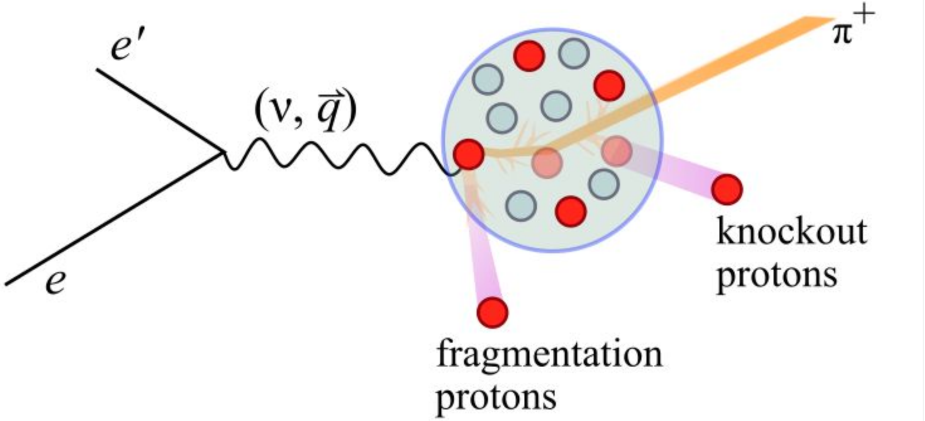
$$Y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$$



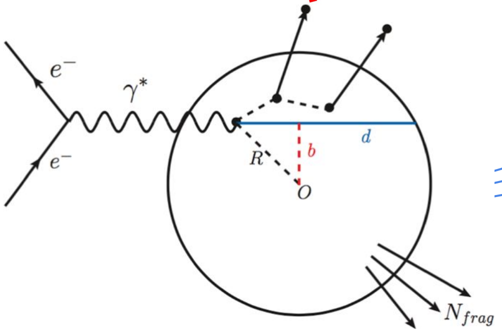
"Slow" knockout protons

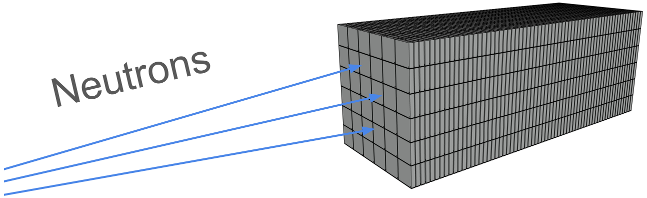
Jefferson Lab

- "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.



ePIC





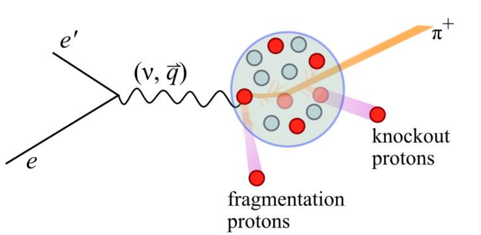
→Boost from nuclear frame to lab frame

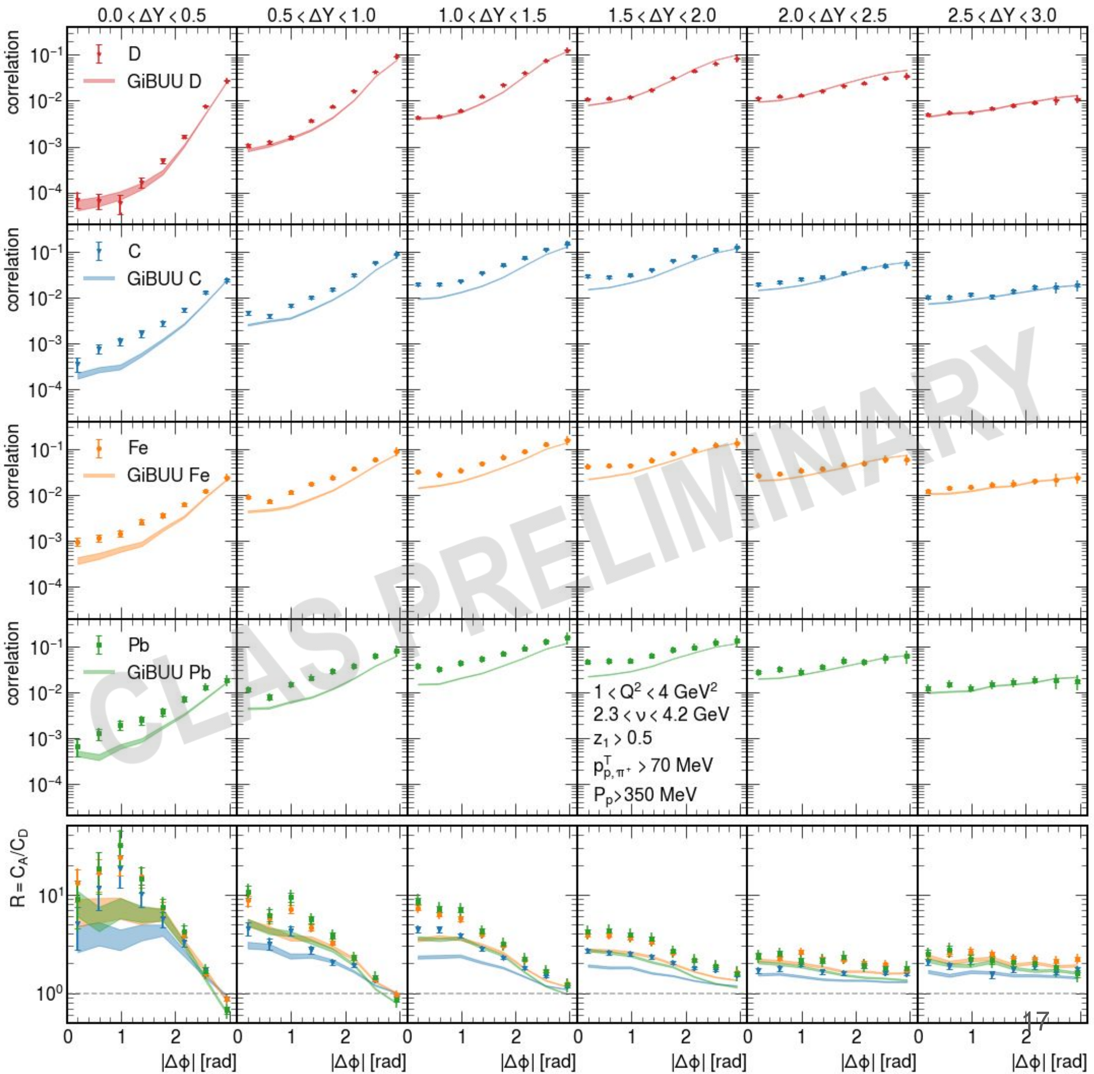
Zero-degree calorimeter

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

Correlation plot

- |Δφ| for the x axis
- ΔY in columns
- Target types as rows
- Bottom row: A/D ratio of correlation functions.

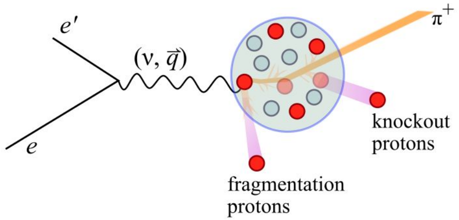


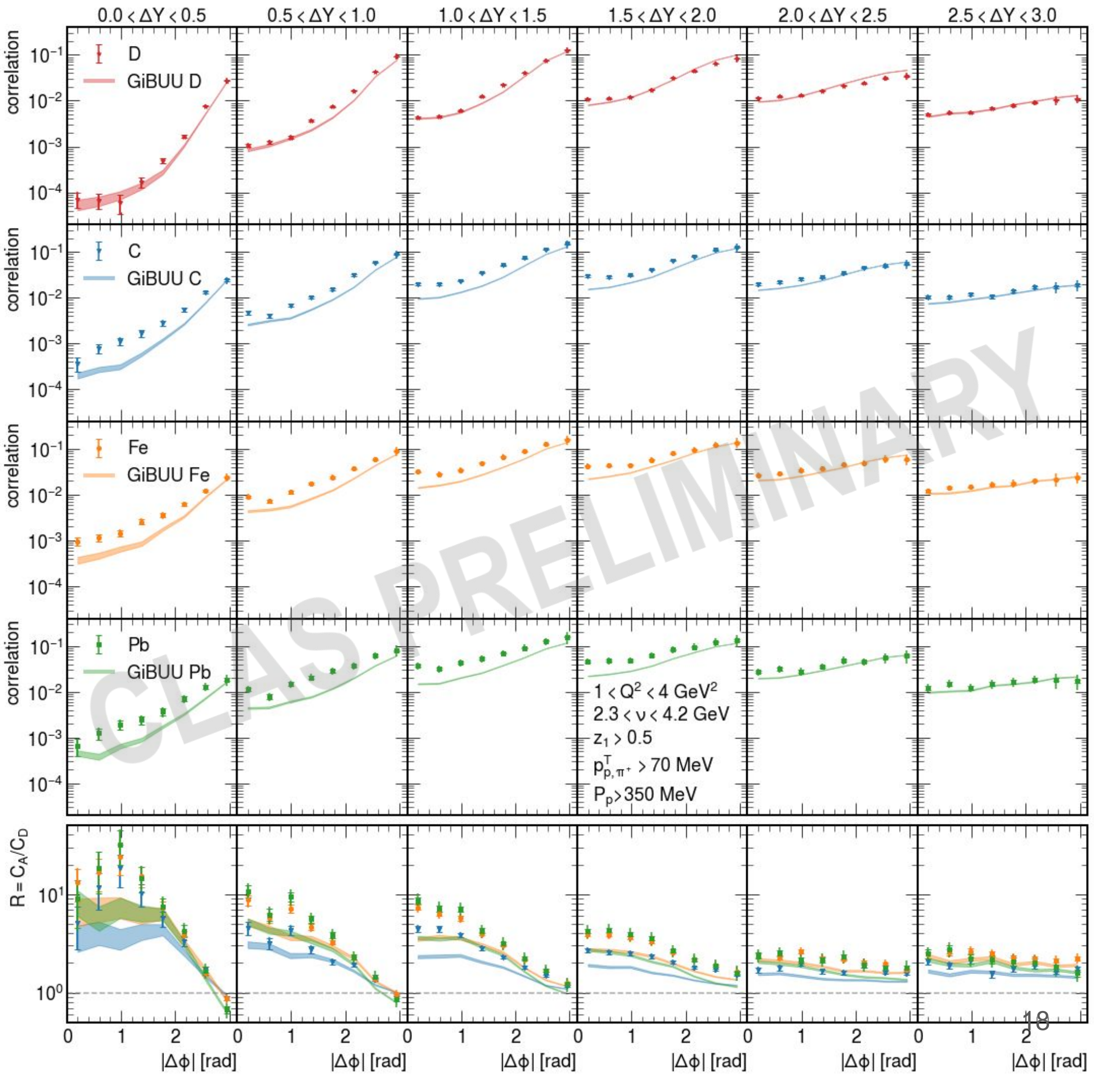


Wider correlation functions for heavier nuclei

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

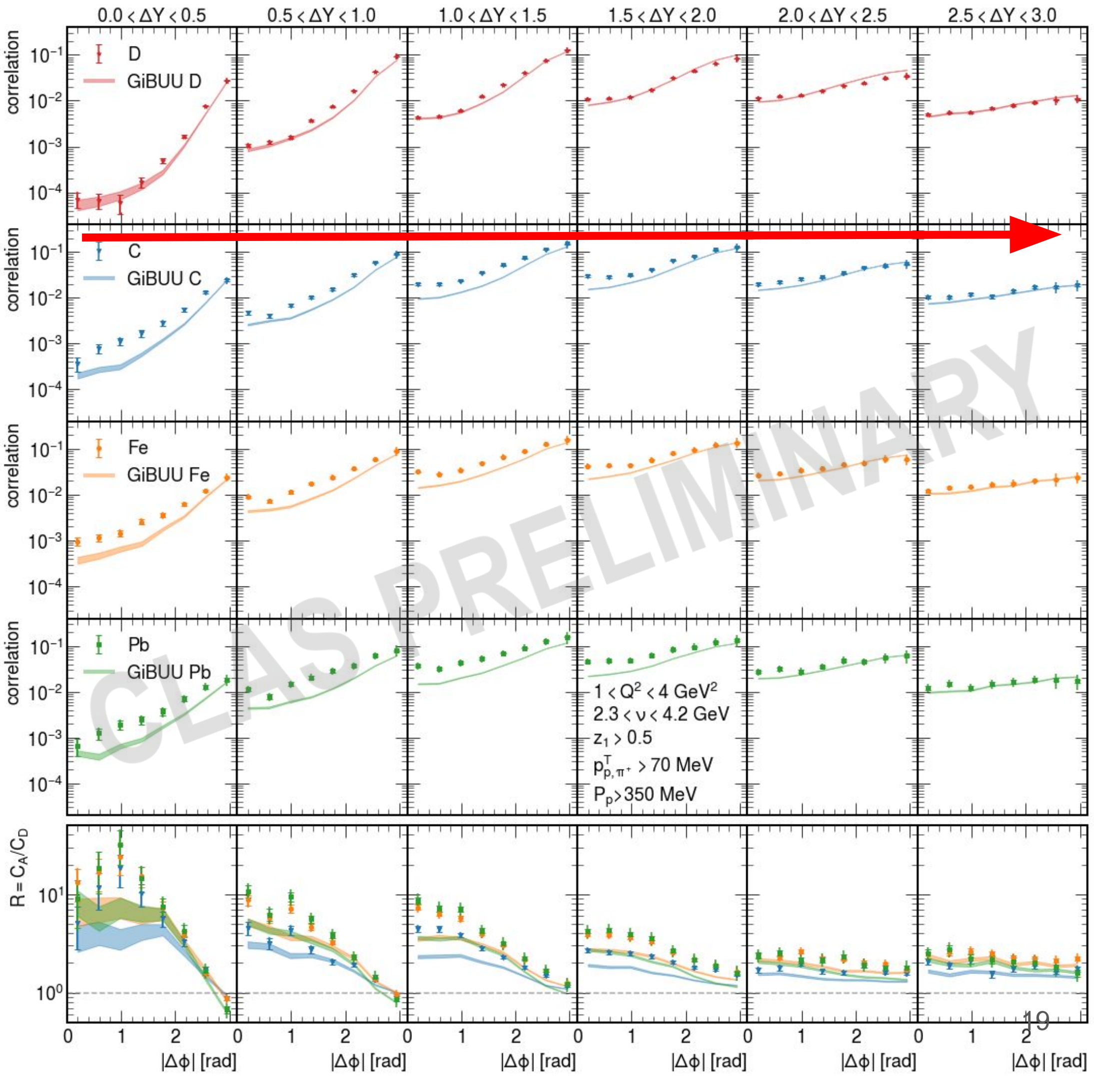
$$Y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$$





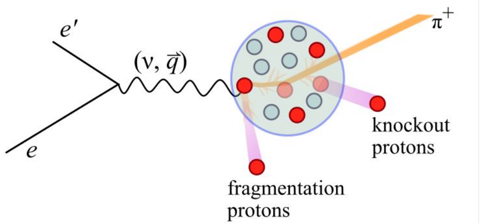
Correlation functions also become wider at larger ΔY

Peaks have largest values at 1.0<ΔY<1.5



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

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

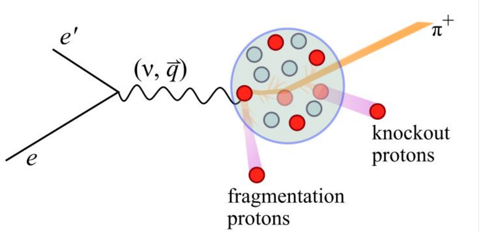


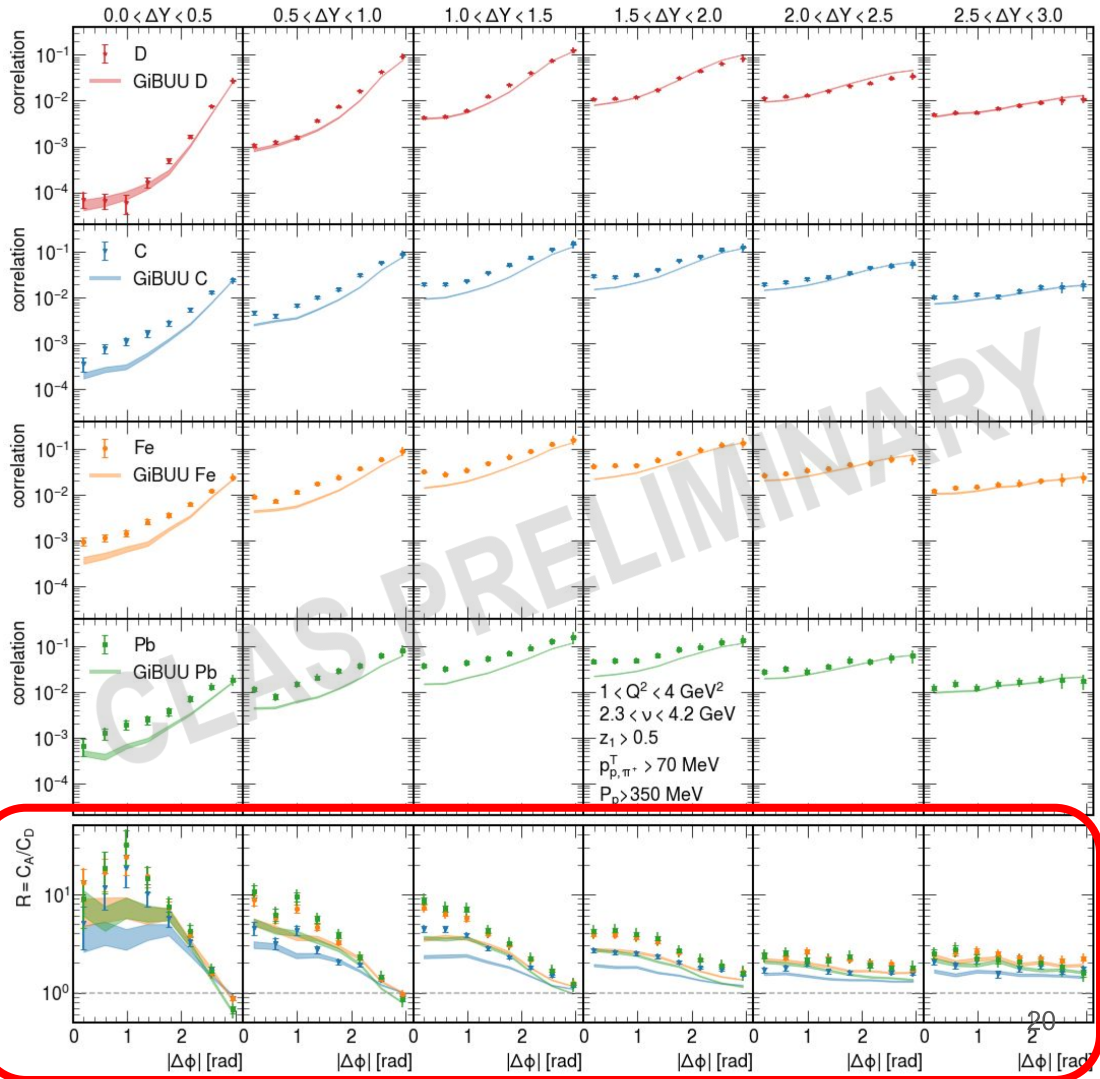
$R=C_A/C_D$ >1 for most bins:

More protons are produced per leading pion in nuclei than in deuterium

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

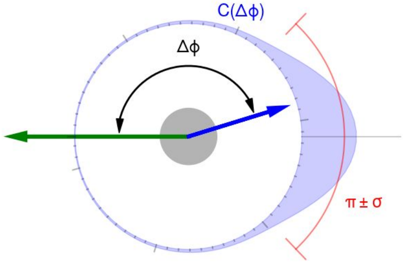
$$Y = \frac{1}{2}\log\frac{E+p_z}{E-p_z}$$





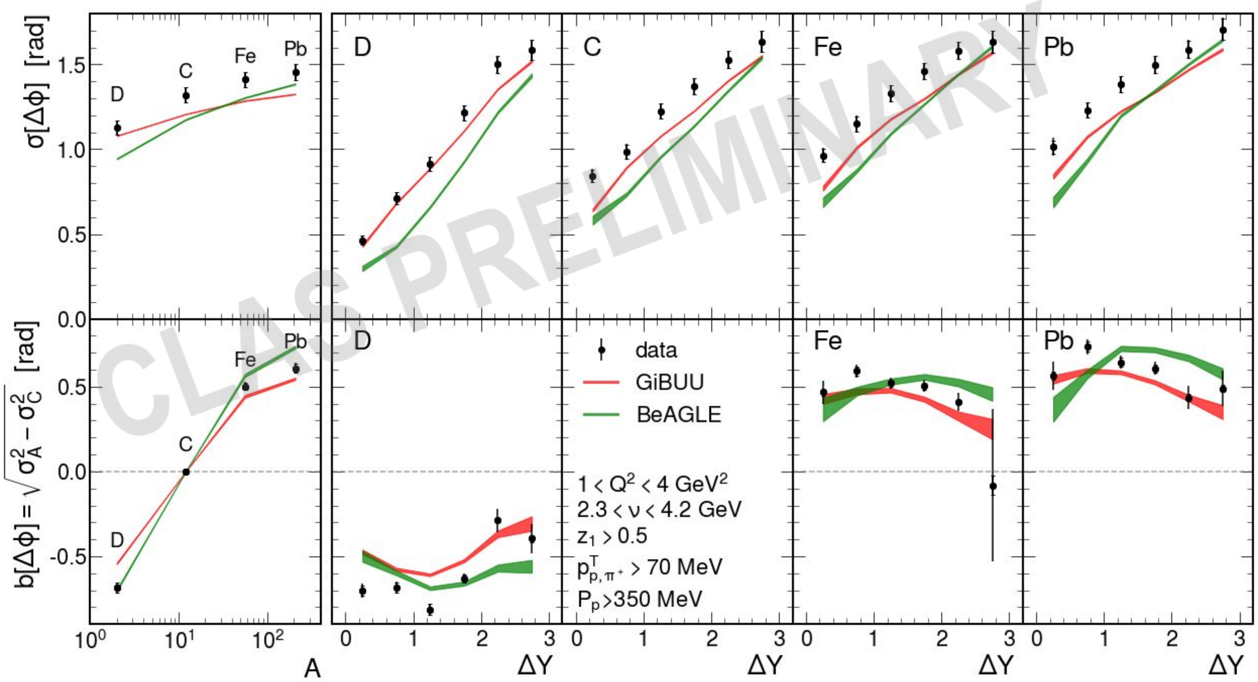
Widths and broadenings

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



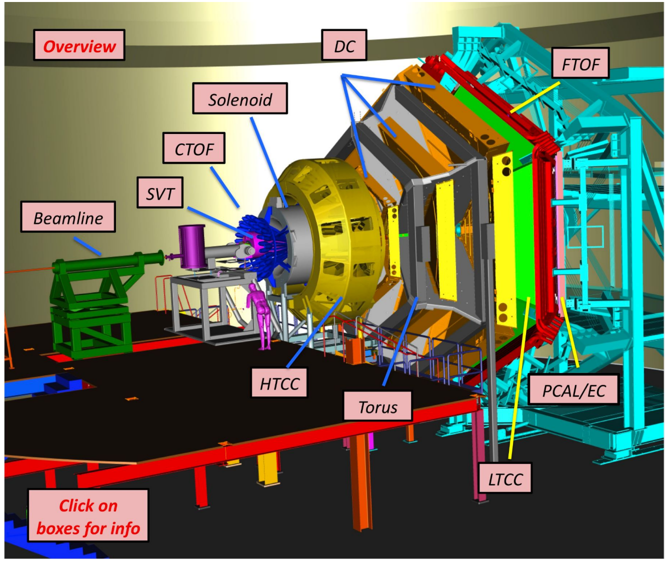
- Widths increase as a function of *A* and also *ΔY*
    - Trends also reproduced by GiBUU and BeAGLE models
- Broadenings defined with respect to carbon:
    - Negative for deuterium

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

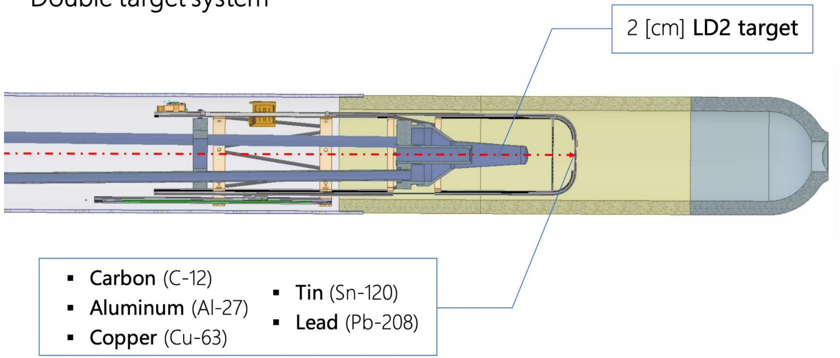


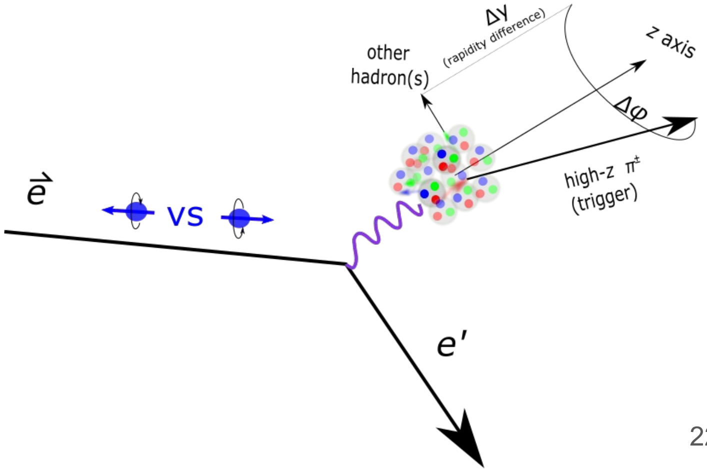
Follow-up measurements with upgraded CLAS12 (Run Group E)

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



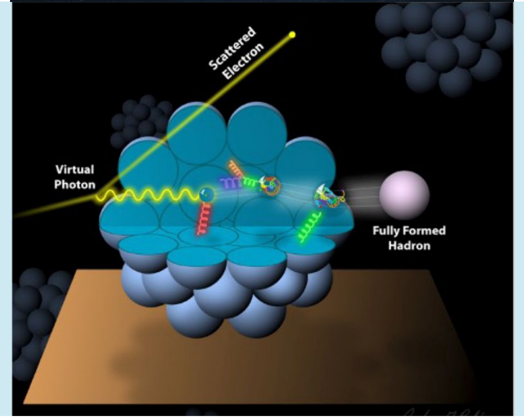
Double target system





Summary

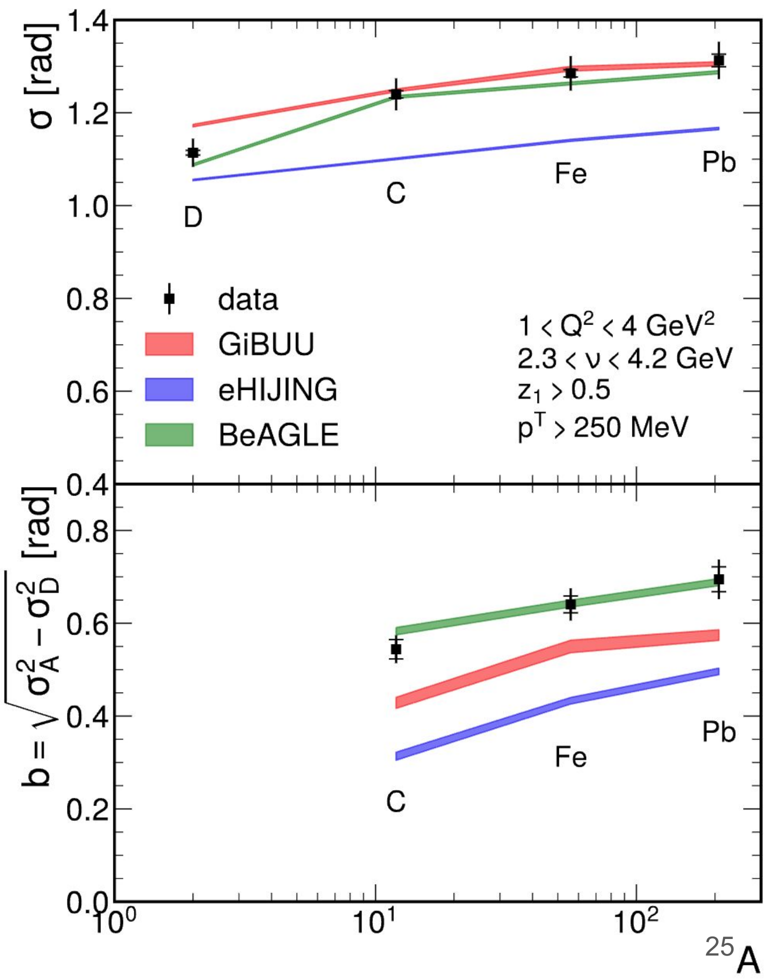
- Di-hadron correlations represents a new tool to explore how hadronization is affected by nuclei
- Current and future analyzes with RGE will seek to answer some of the questions raised in the 2023 LRP
    - How are the various hadrons produced in a single scattering process correlated with one another and how does hadronization change in a dense partonic environment?
    - What are the timescales of color neutralization and hadron formation?



Backup slides

Models

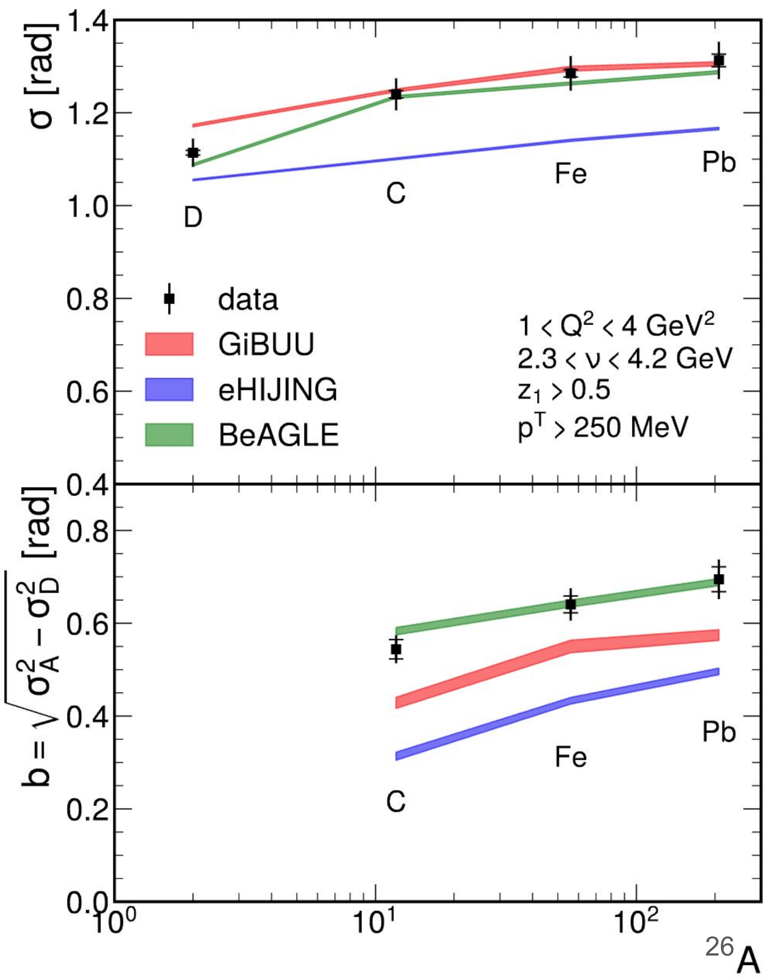
- GiBUU
  - Final-state interactions
  - Absorption
  - Hadron production mechanisms
  - Pre-hadron degrees of freedom
  - Color transparency
  - Nuclear shadowing



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

Models

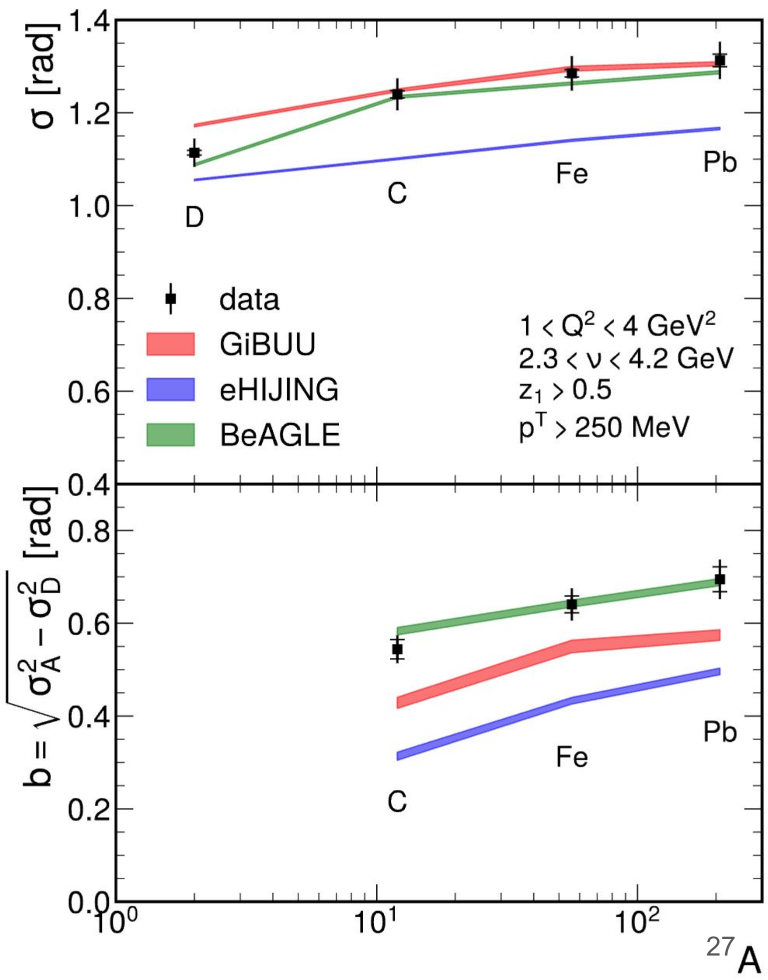
- eHIJING
  - Based on Pythia8
  - Interaction between hadrons and the nuclear medium proportional to the nuclear TMD PDF of gluons.



arXiv:2304.10779

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