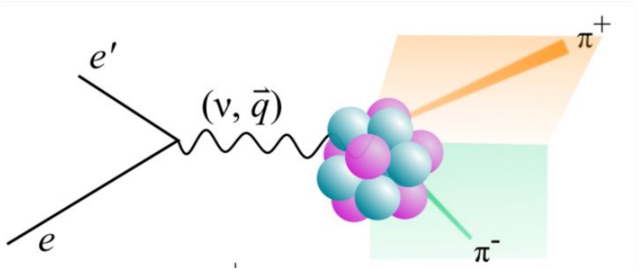
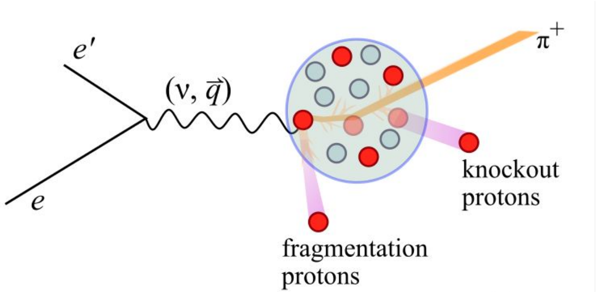
Di-Hadron Correlations in Nuclei

Dr. Sebouh Paul
UC Riverside
11/13/2024





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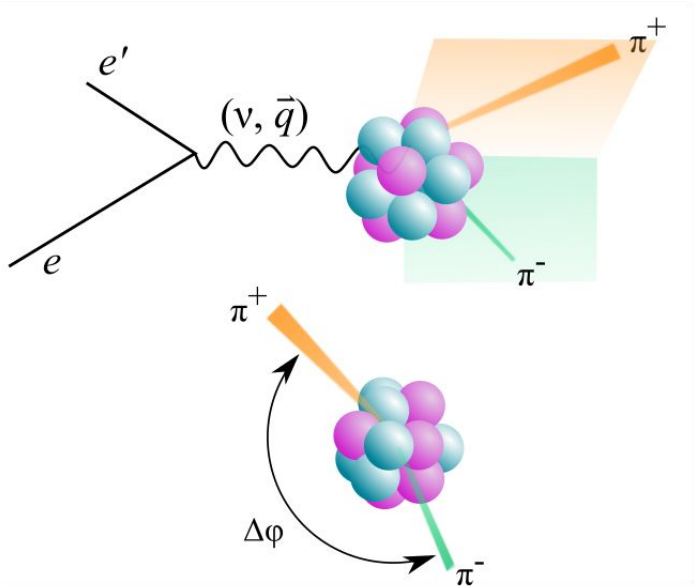
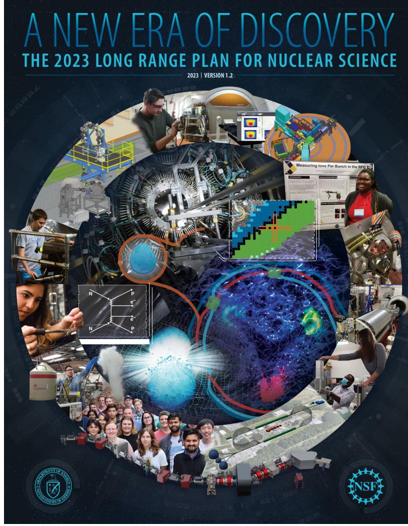
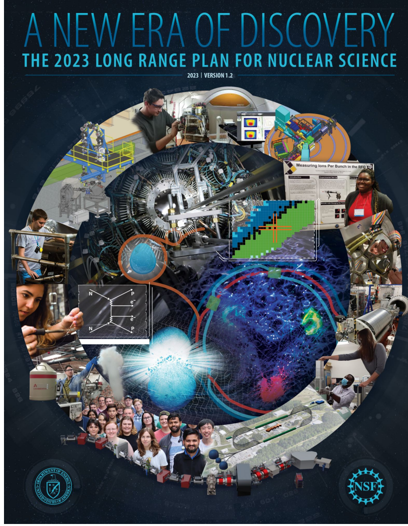
CEBAF Large Acceptance Spectrometer

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

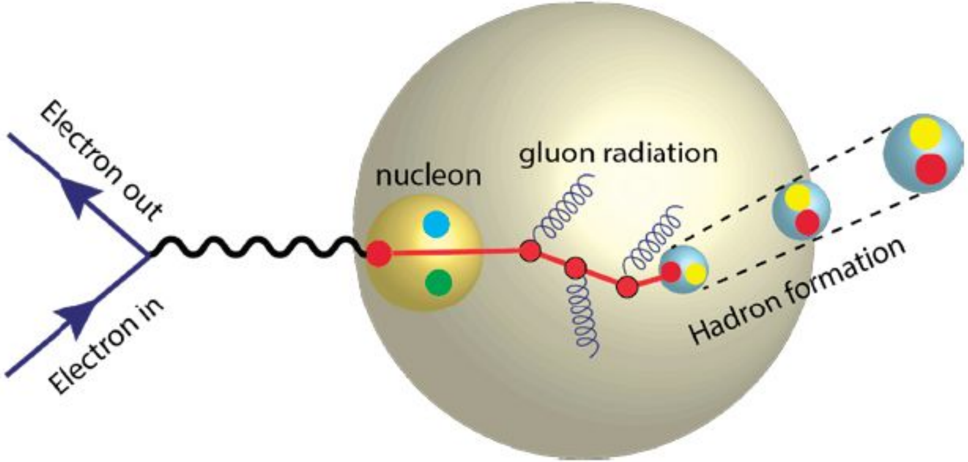




… and how does hadronization change in a dense partonic environment?



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



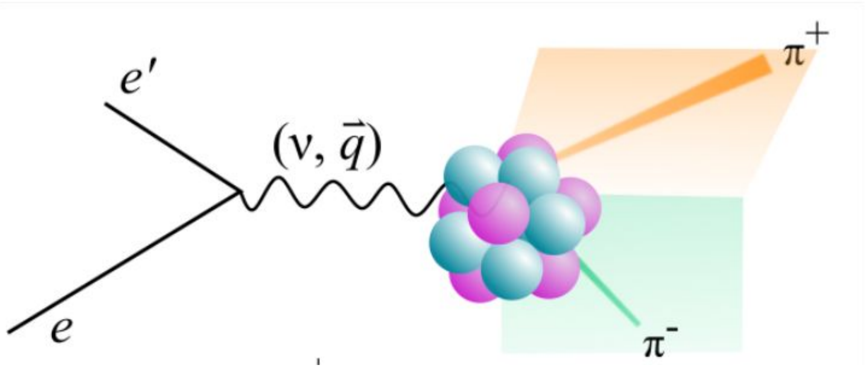
Event topologies

Di-pion:

- High energy π+ and low energy π-

Phys. Rev. Lett. **129**, 182501

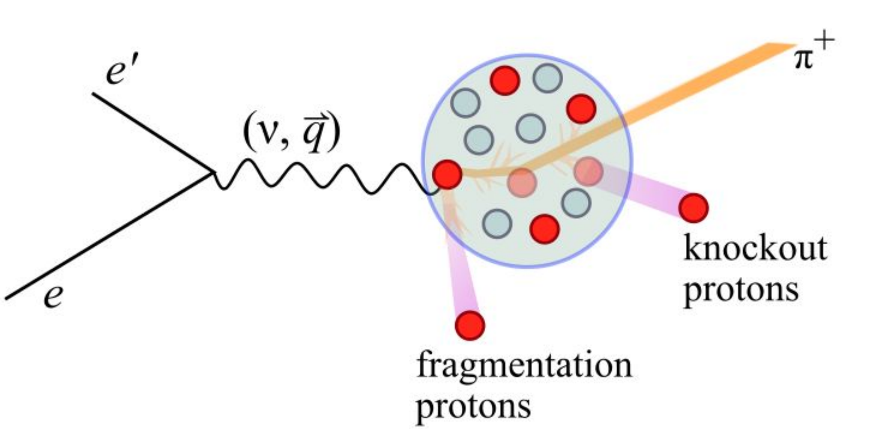
https://arxiv.org/abs/2406.14387, in review at PRC



Pion+proton

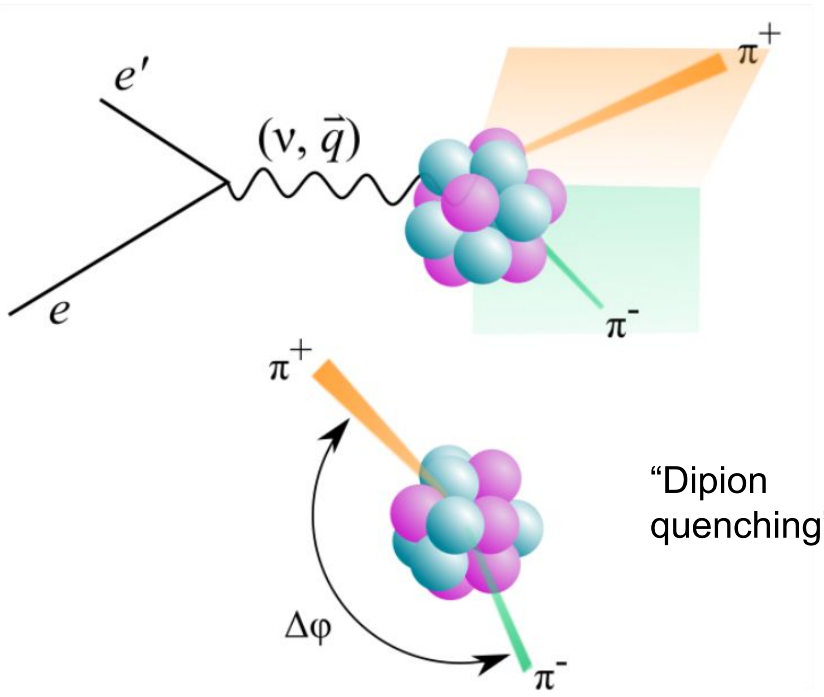
- High energy π+ and knocked-out proton (or proton from fragmentation)

Analysis note in review since XXX

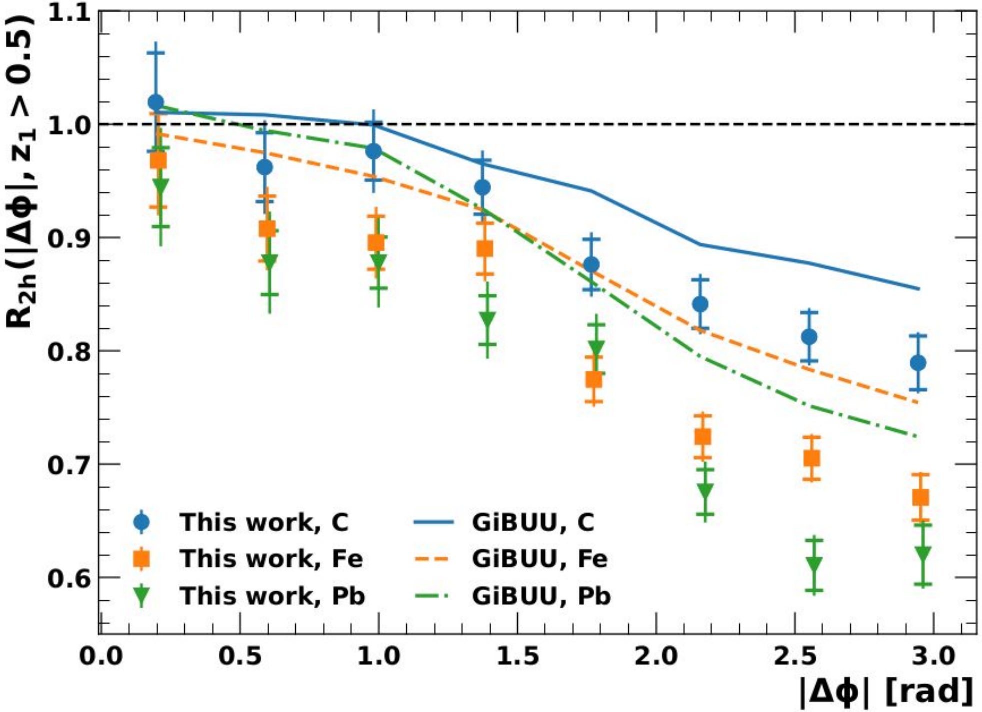


Earlier results …

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



"Dipion quenching"



Phys. Rev. Lett. **129**, 182501

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

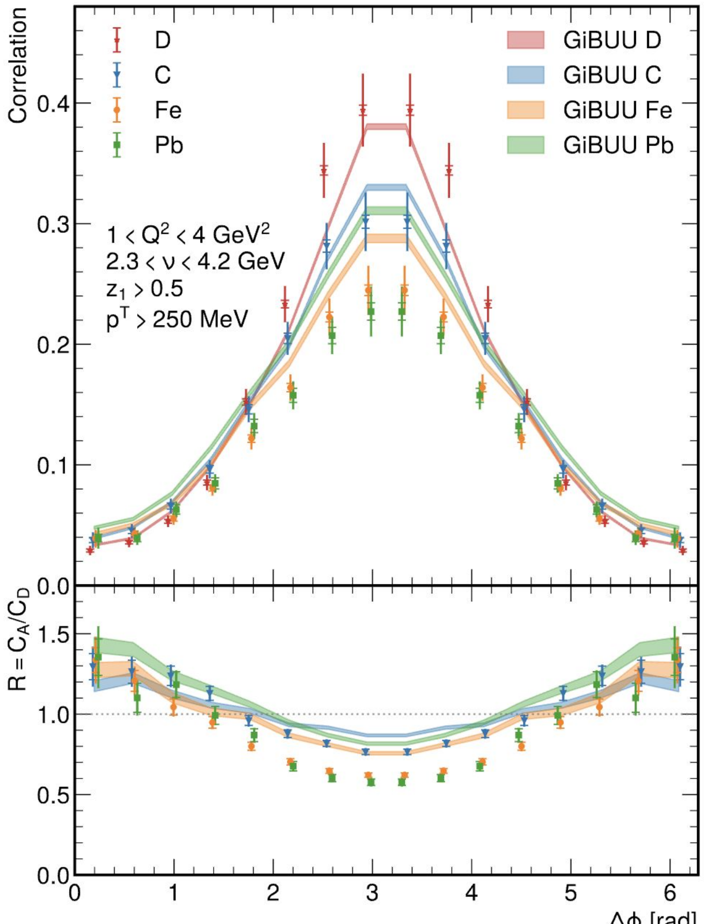
Leading π^+, subleading π^-

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

https://arxiv.org/abs/2406.14387

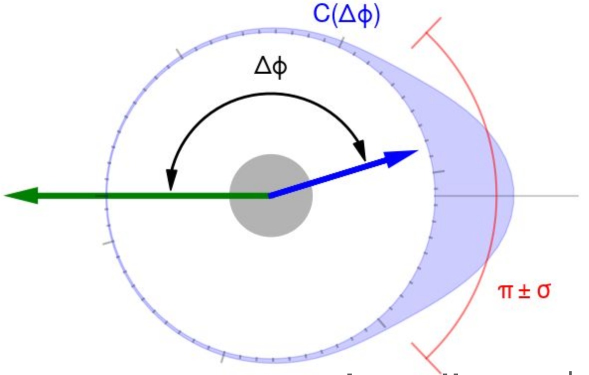


Derived quantities: RMS widths and broadenings

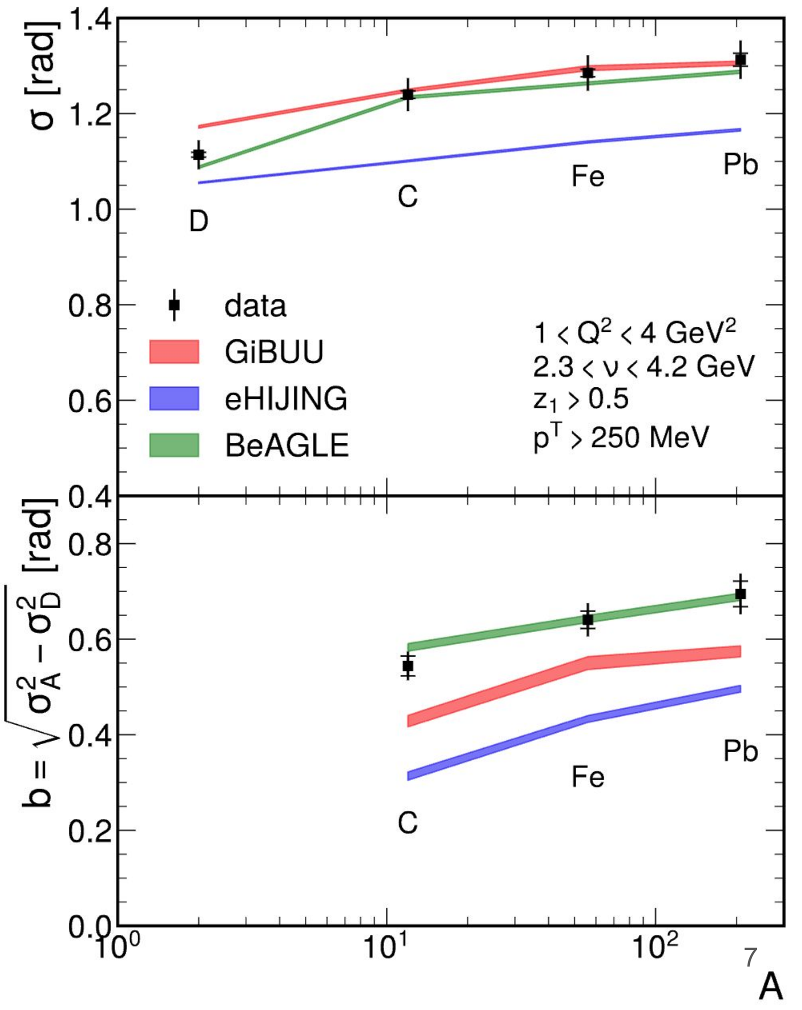
RMS width:

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

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

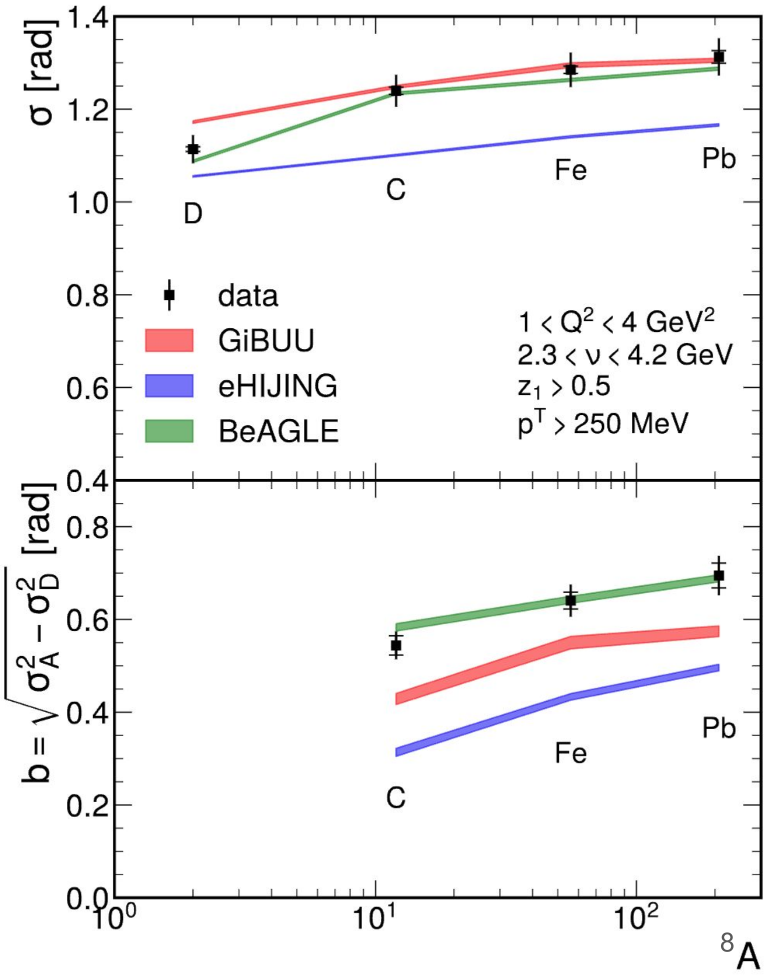


Leading π^+, subleading π^-



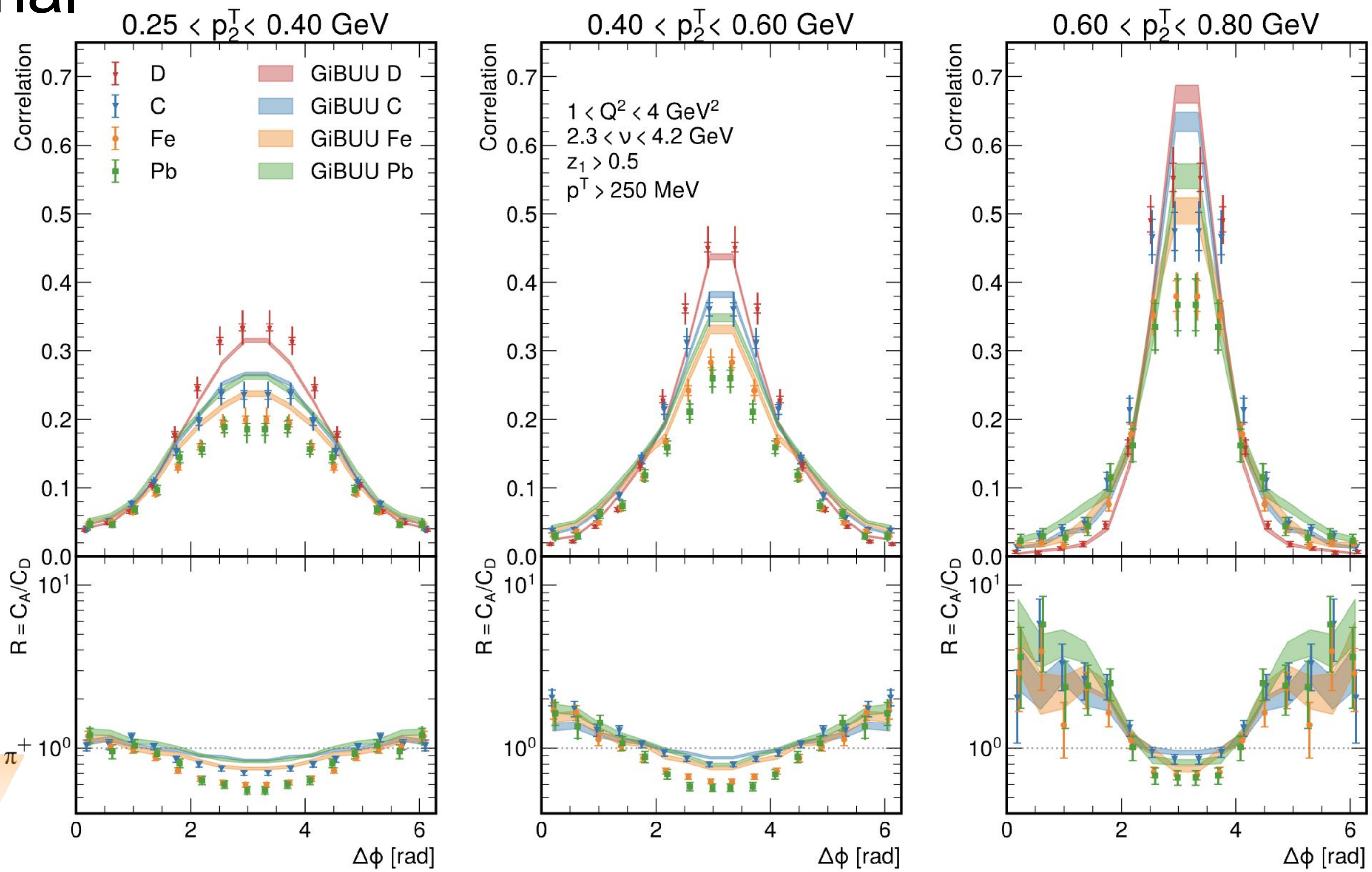
Derived quantities: RMS widths and broadenings

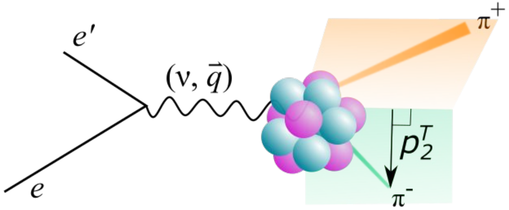
- RMS widths and broadening increase with larger nuclei with weak, log-like A dependence.
- Most of these models are new, developed for the EIC rather than JLab energies, yet predict this trend correctly



Multi-dimensional measurements

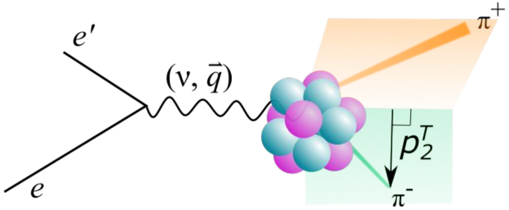
- At large $p^T{}_2$, the correlation function peak becomes more narrow
- Nuclear effects strongly depend on pT2

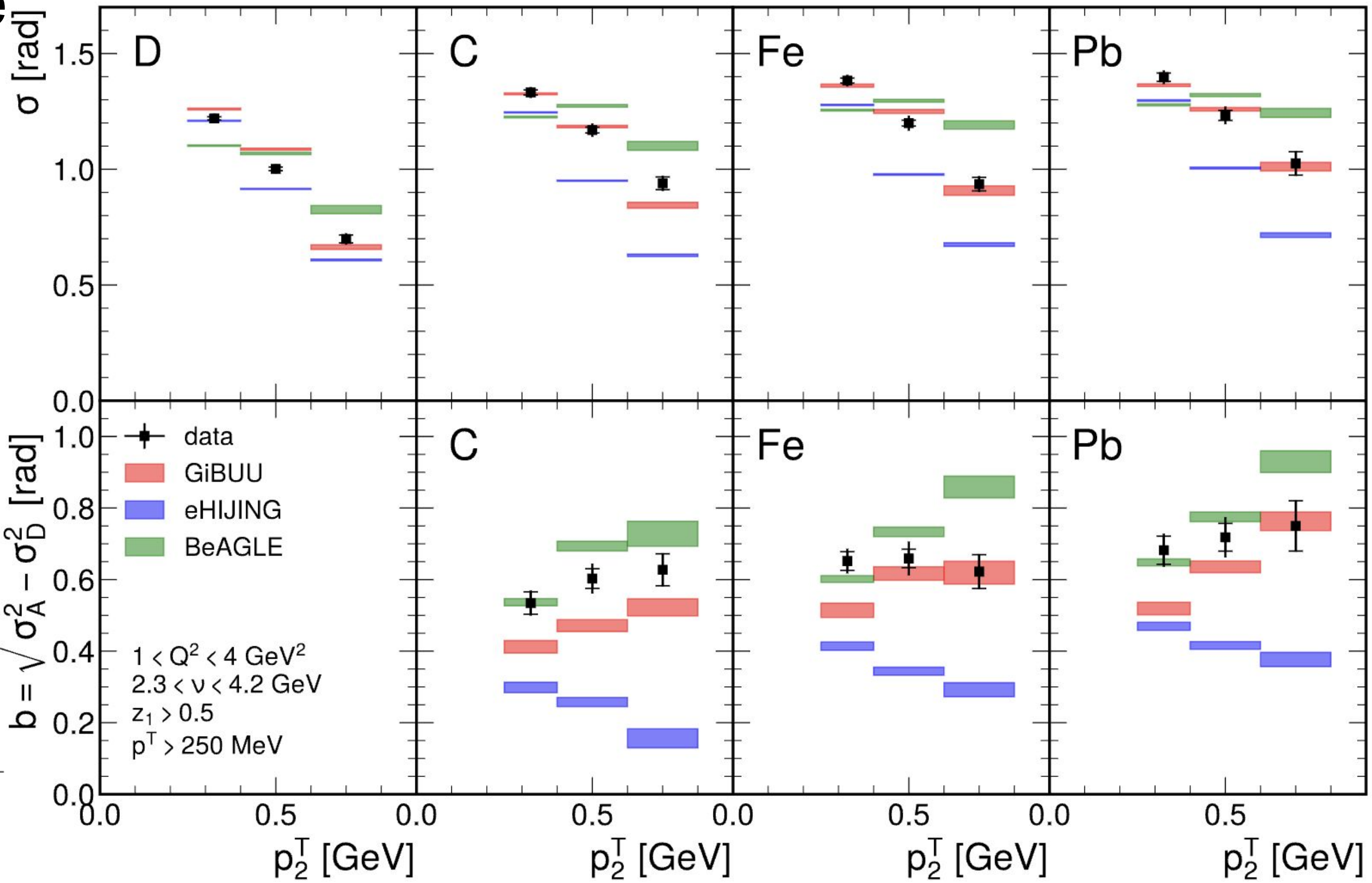




p_2^T dependence

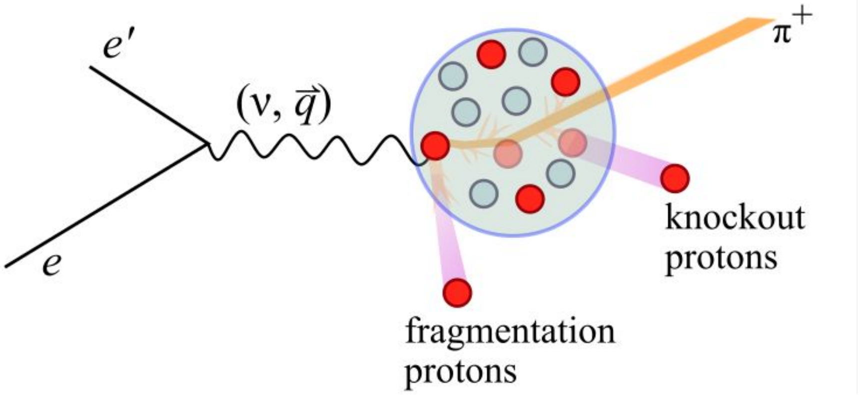
- Models predict different trends in the broadening vs p_2^T, which demonstrates the discriminating power of these measurements





How does the nucleus react to a fast quark?

Protons proxy for "nuclear response"

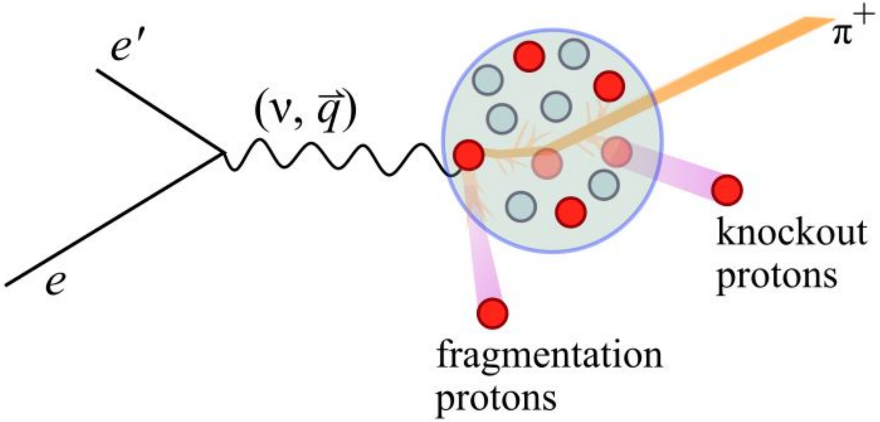


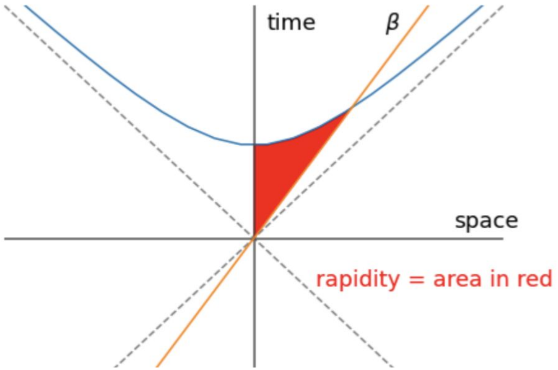
Pion-proton analysis
(in analysis review, round 1)

- 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*

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

$$Y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

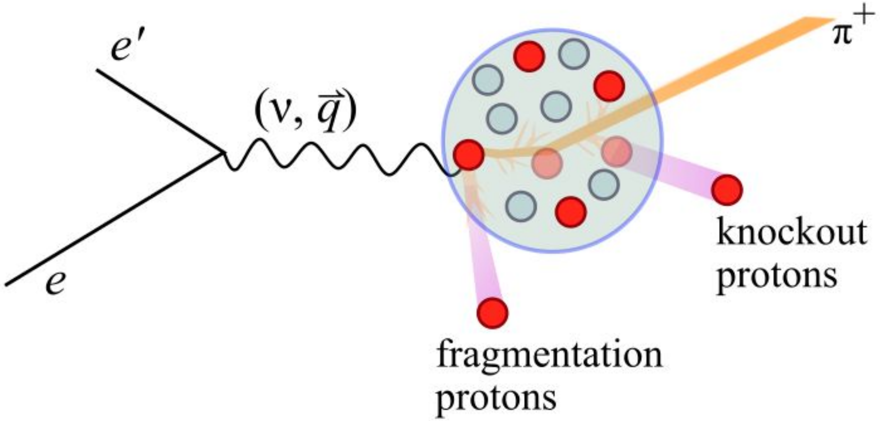




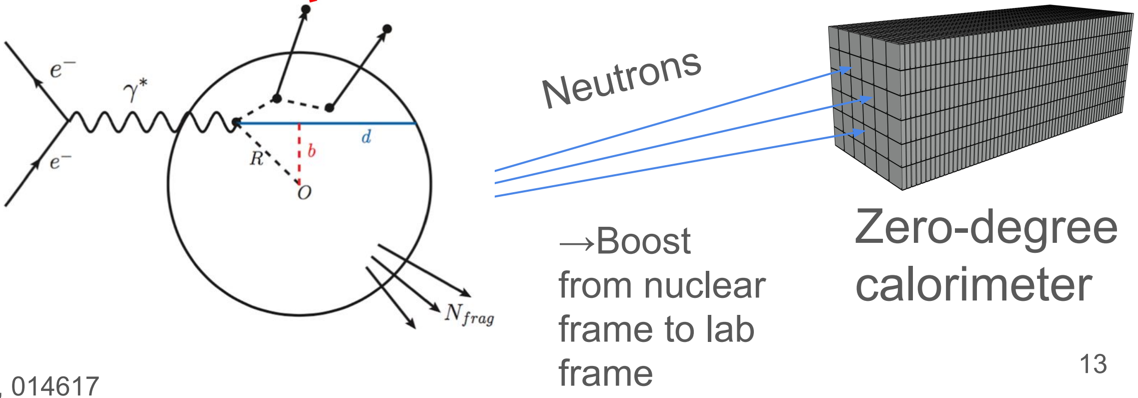
“Slow” knockout protons

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 from 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.

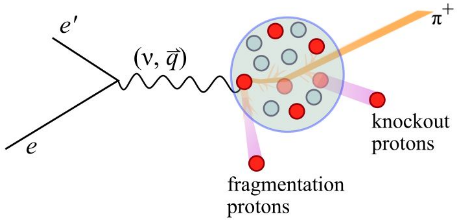


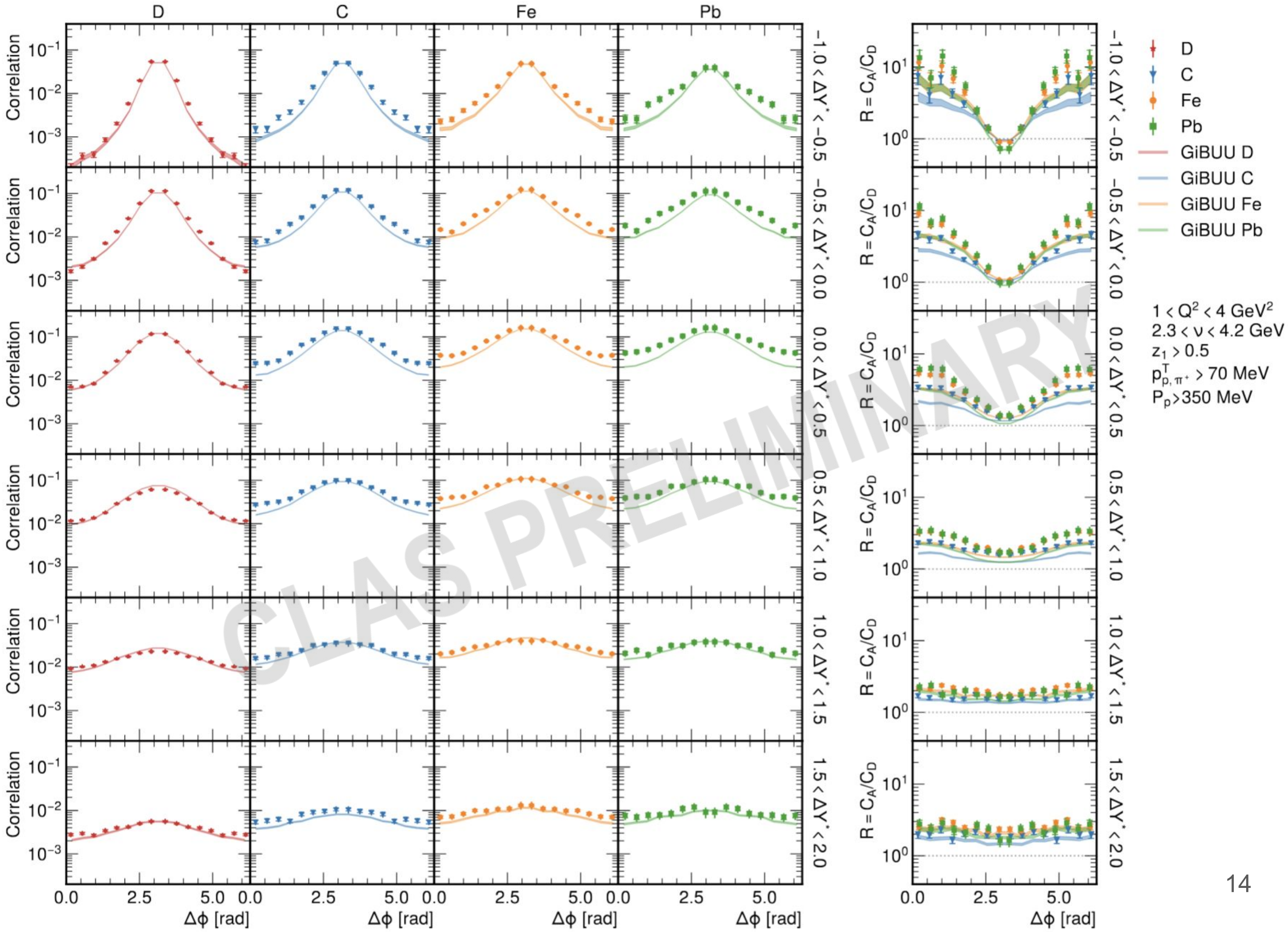
ePIC



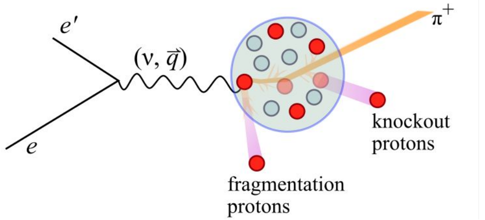
*Phys. Rev. C **106**, 045202, Phys. Rev. C **101**, 014617

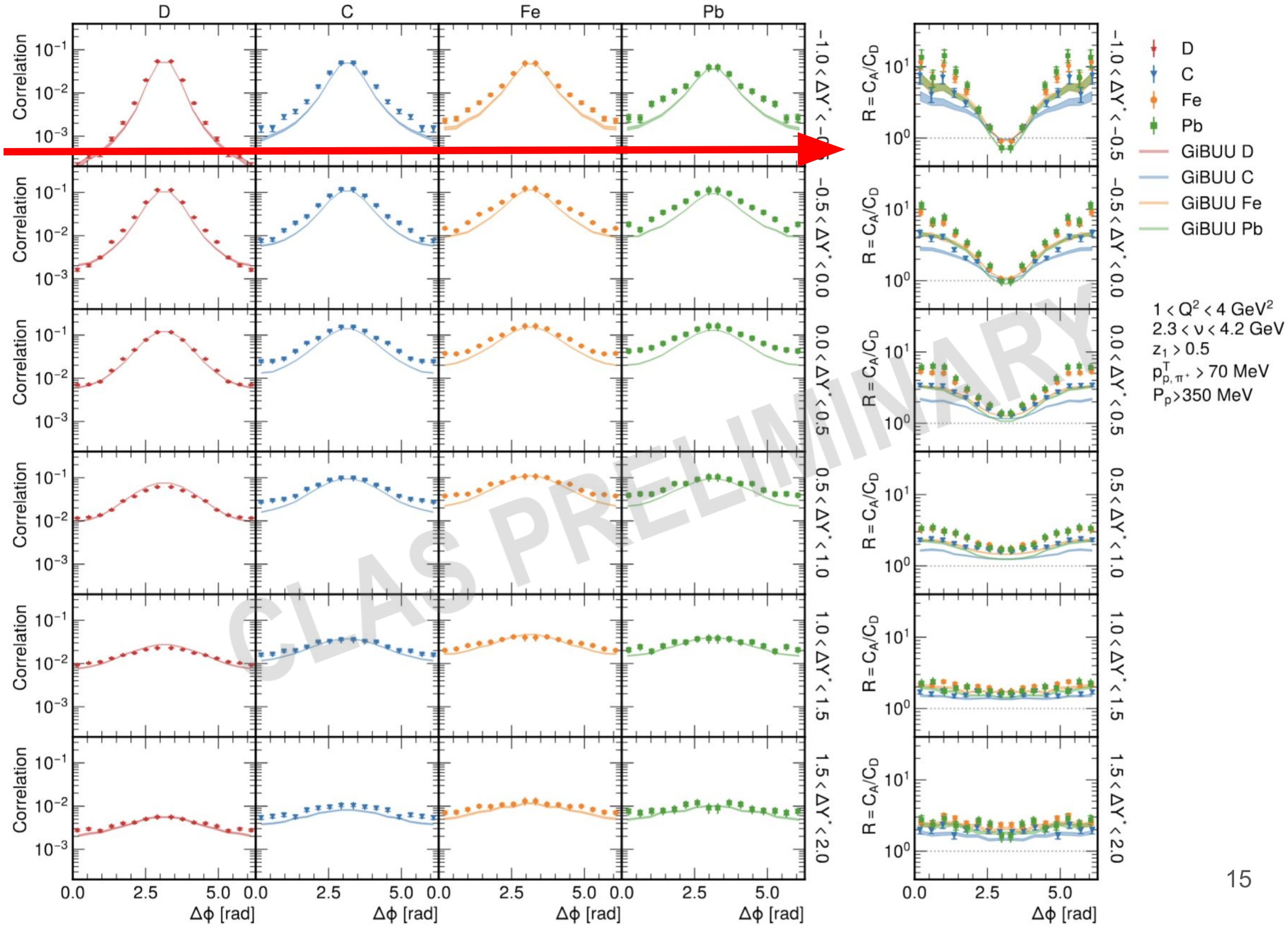
Pion-Proton correlations





Wider correlation functions for heavier nuclei



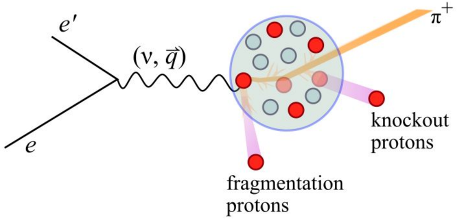


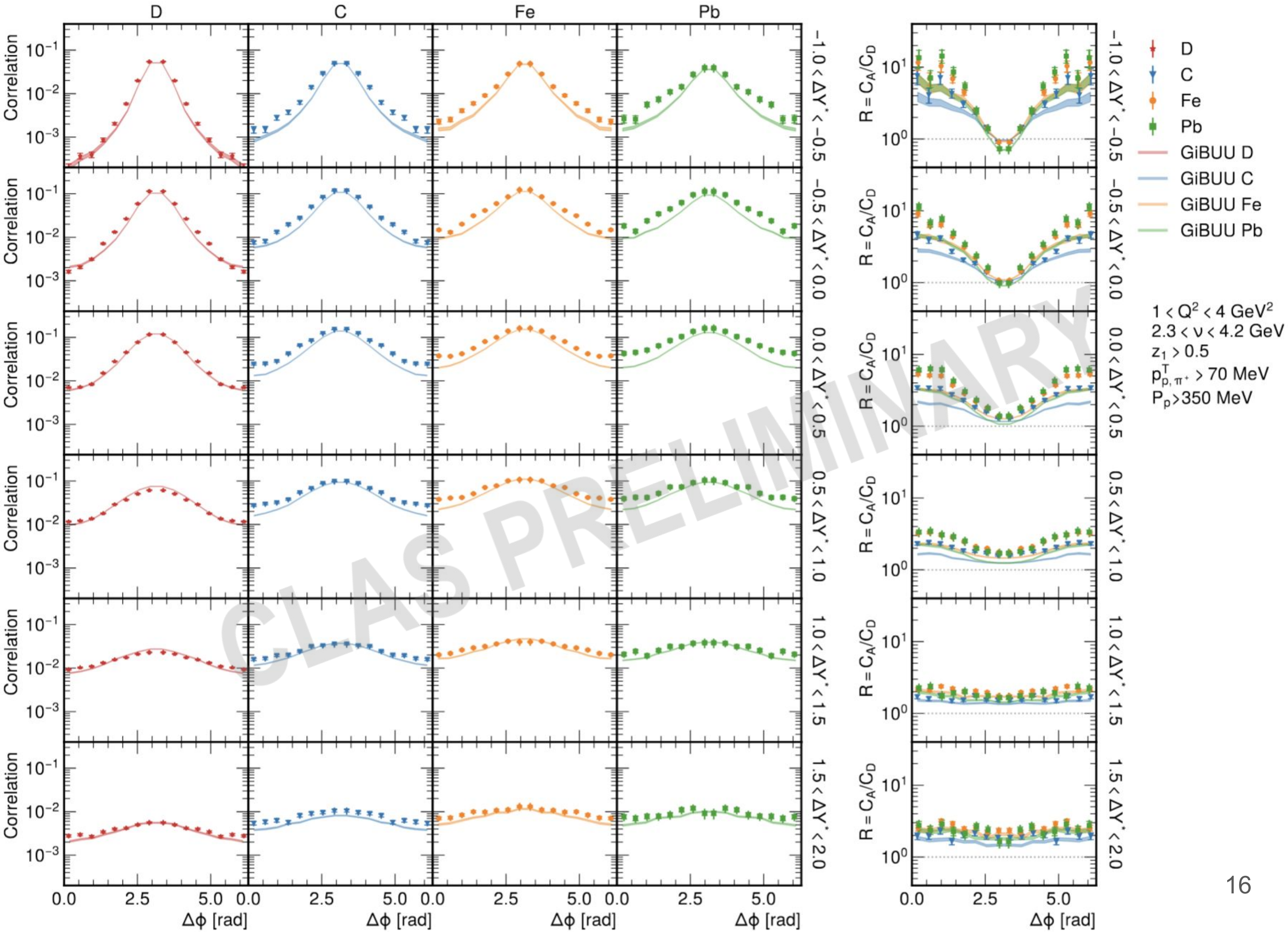
Correlation functions also become wider at larger ΔY*

Also peaks are at maximum height at ΔY*~0

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

$$Y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$



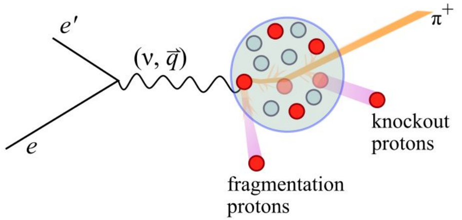


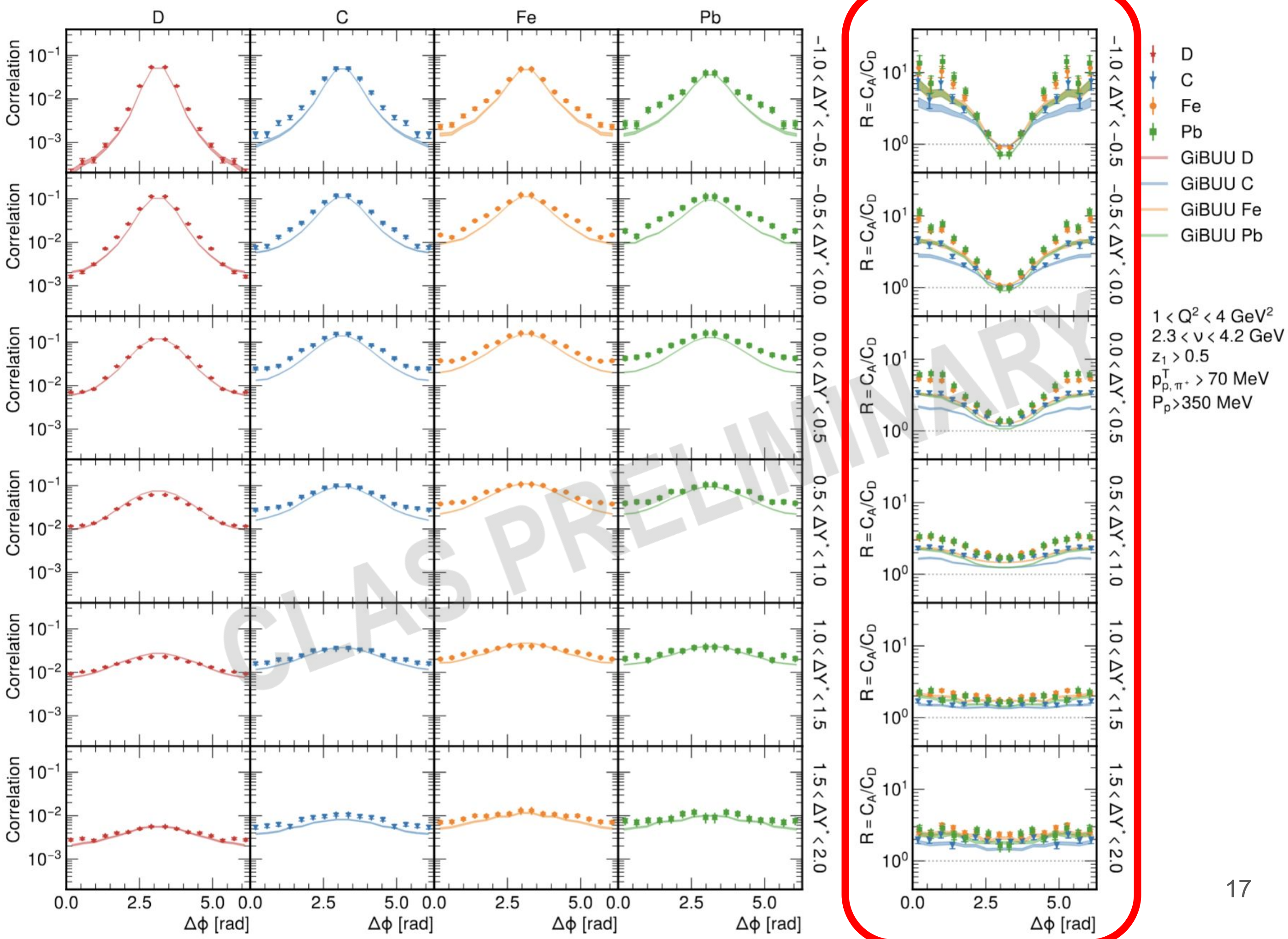
R=C_A/C_D >1 for most bins:

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

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

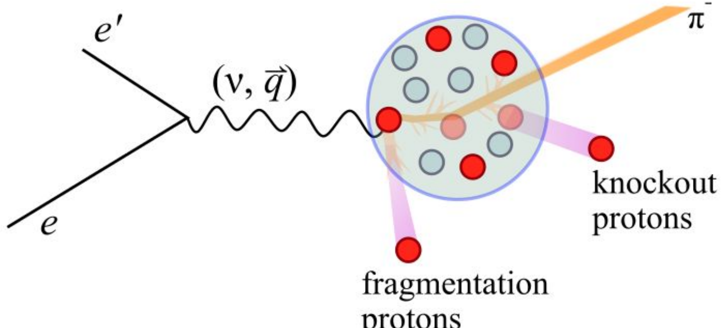
$$Y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

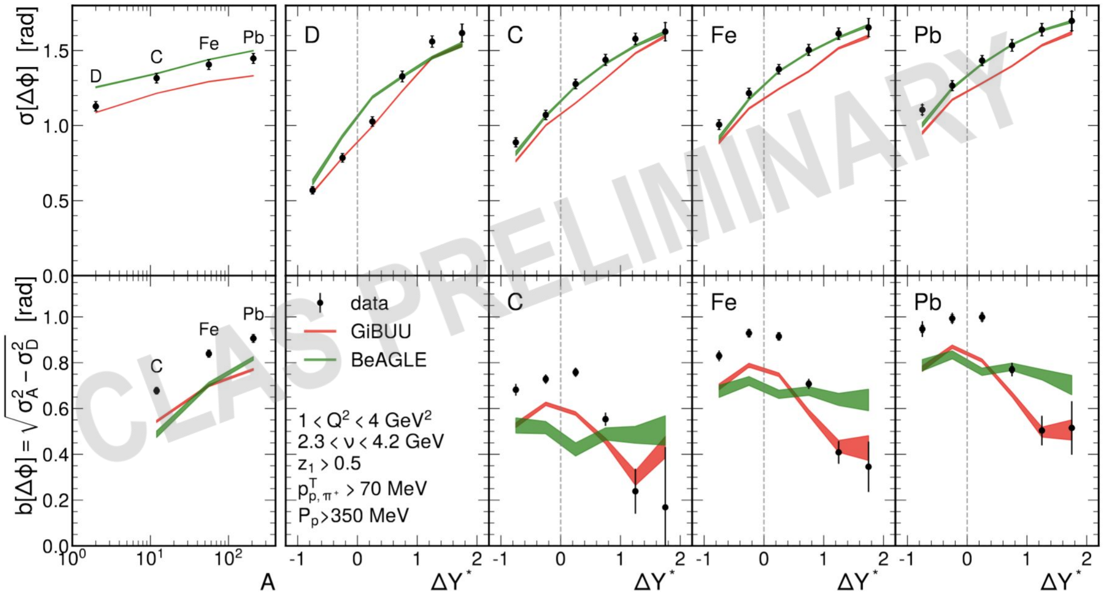




Width and broadenings

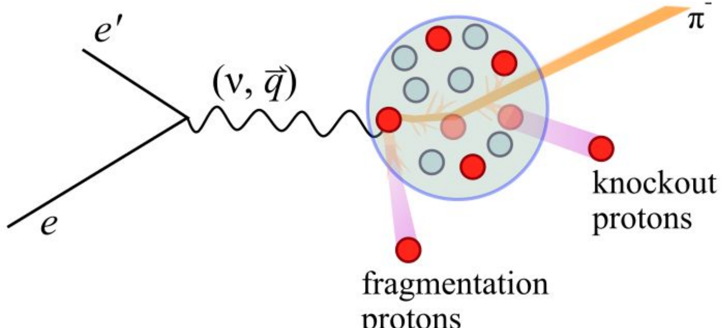
- σ[Δφ] increases a function of rapidity separation
- Broadening at maximum near ΔY*=0

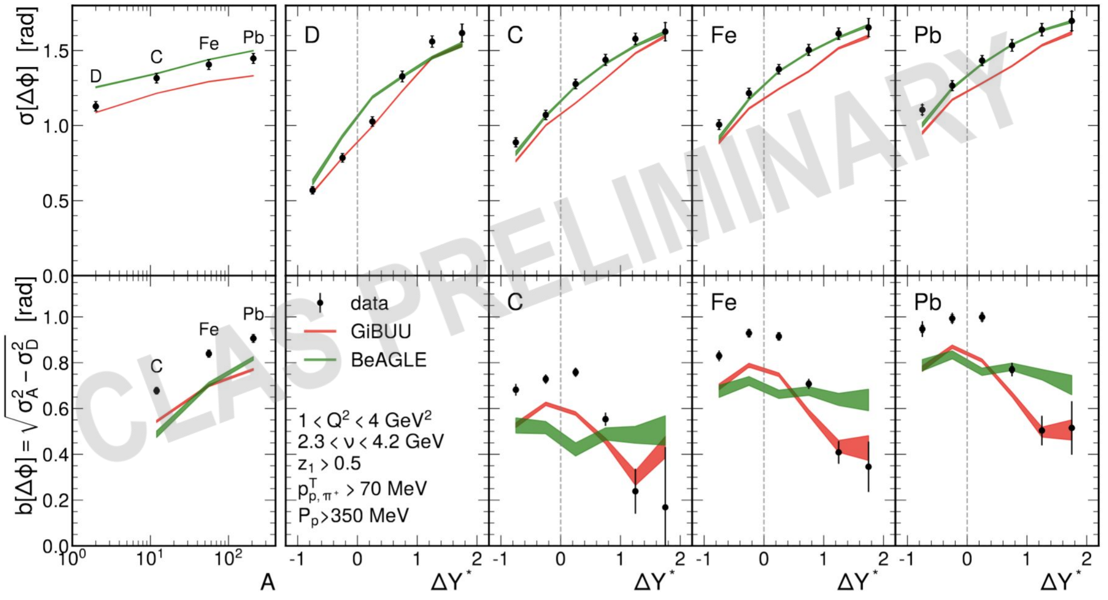




Widths and broadenings

- Both the GiBUU and BeAGLE models have decent predictions for these quantities
- Could be further fine-tuned

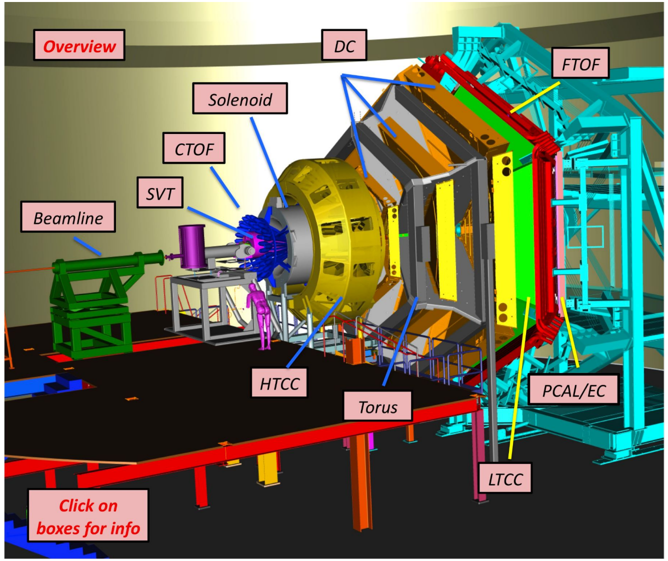


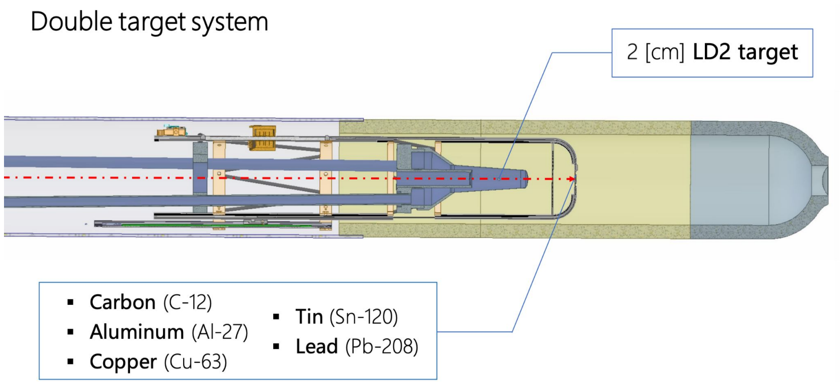


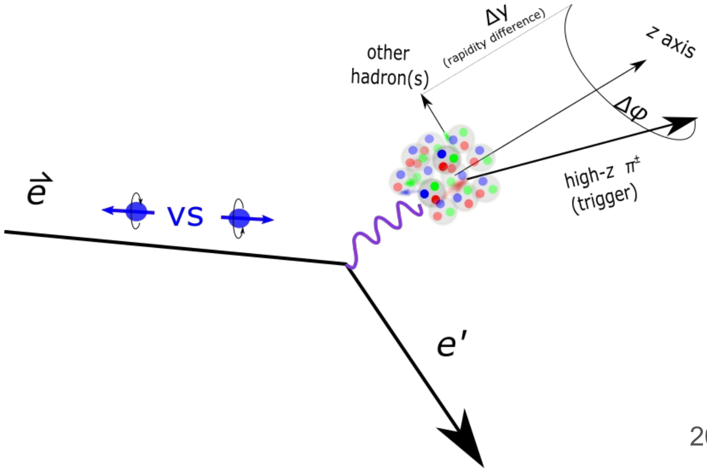
Follow-up measurements with upgraded CLAS12 (Run Group E)

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

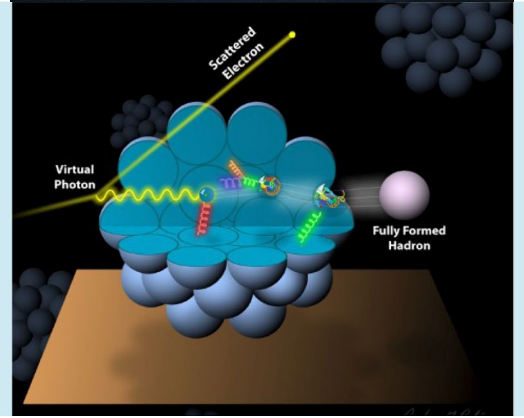






Summary

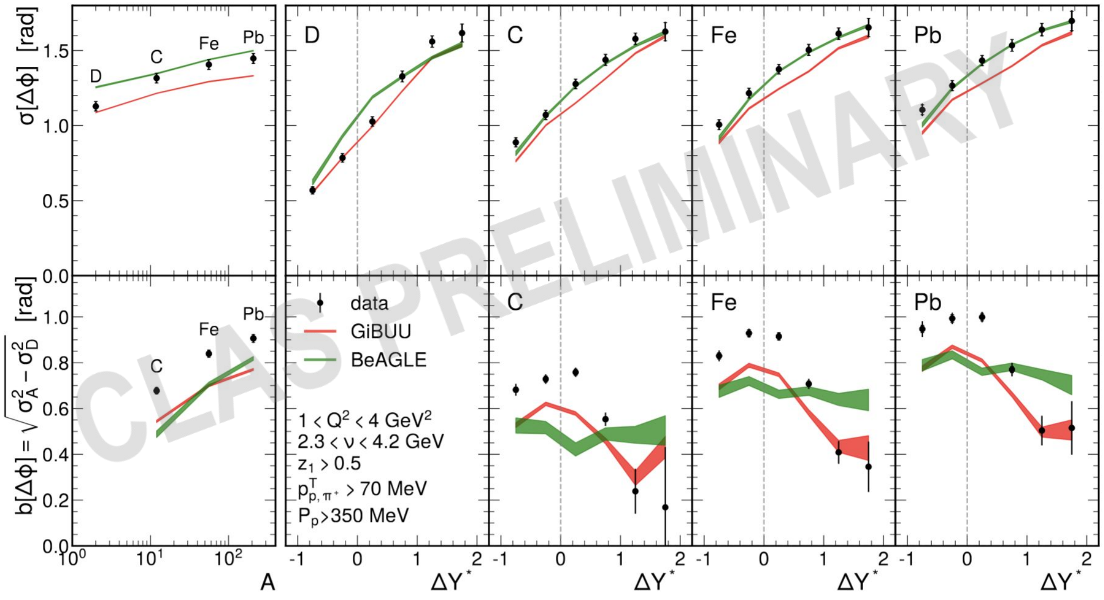
- Di-hadron correlations represents a new tool to explore how hadronization is affected by nuclei
- Current and future analyzes with RGE will seek to answer some of the questions raised in the 2023 LRP
    - How are the various hadrons produced in a single scattering process correlated with one another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



Backup

Models

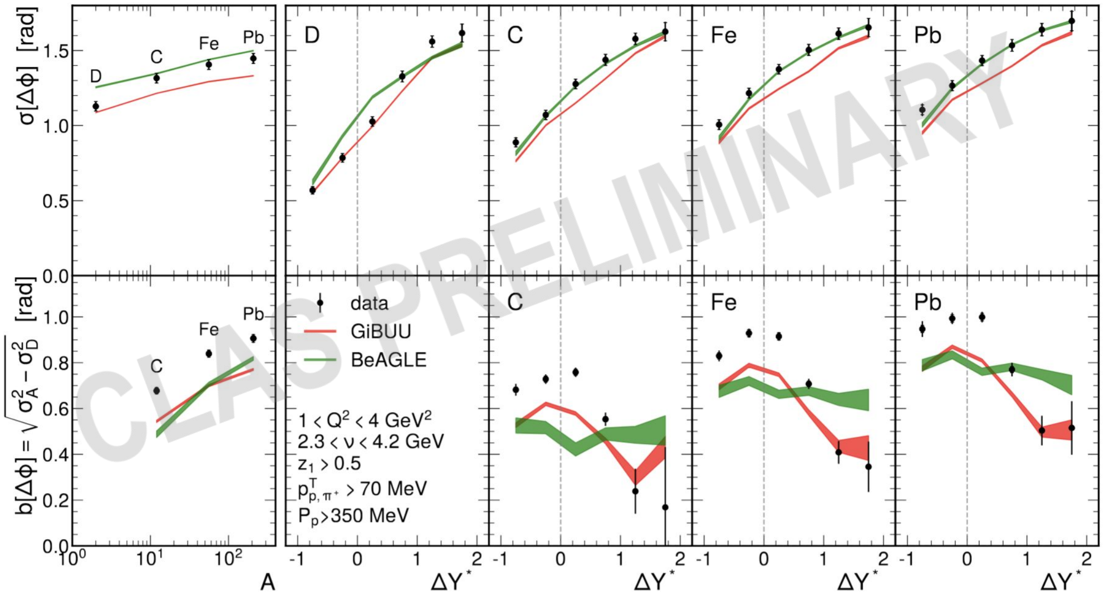
- GiBUU
  - Final-state interactions
  - Absorption
  - Hadron production mechanisms
  - Pre-hadron degrees of freedom
  - Color transparency
  - Nuclear shadowing



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

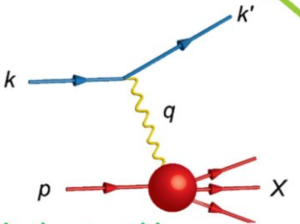
Models

- 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)



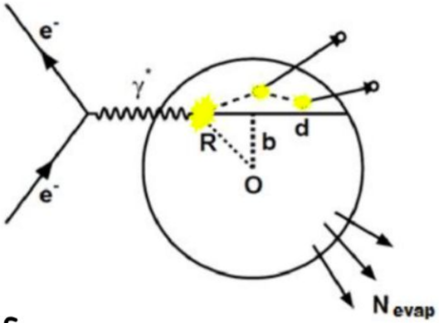
https://doi.org/10.1103/PhysRevD.106.012007

We are using BeAGLE (**B**enchmark **eA** **G**enerator for **LE**ptoproduction) package for the e+A event simulation.

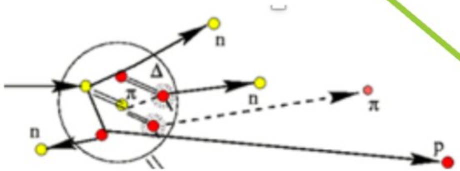


Primary interaction

Primary interaction treated by **PYTHIA** hard collision.

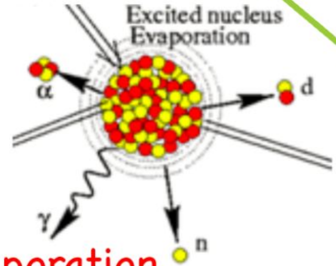


Cascade process handled by **DPMJET**.



Intra-nuclear cascade

Target remnant evaporation and break up included by **FLUKA**.



Nuclear remnant evaporation

Copied from …

Collision geometry and breakup determination in eA collisions

Wan Chang @ BNL & CCNU

Joint CFNS & RBRC Workshop on Physics and Detector Requirements at Zero-Degree of Colliders

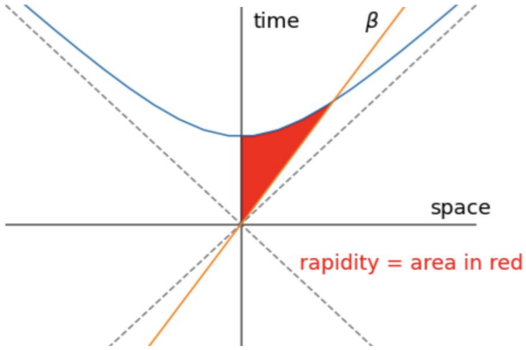
September 24-26, 2019

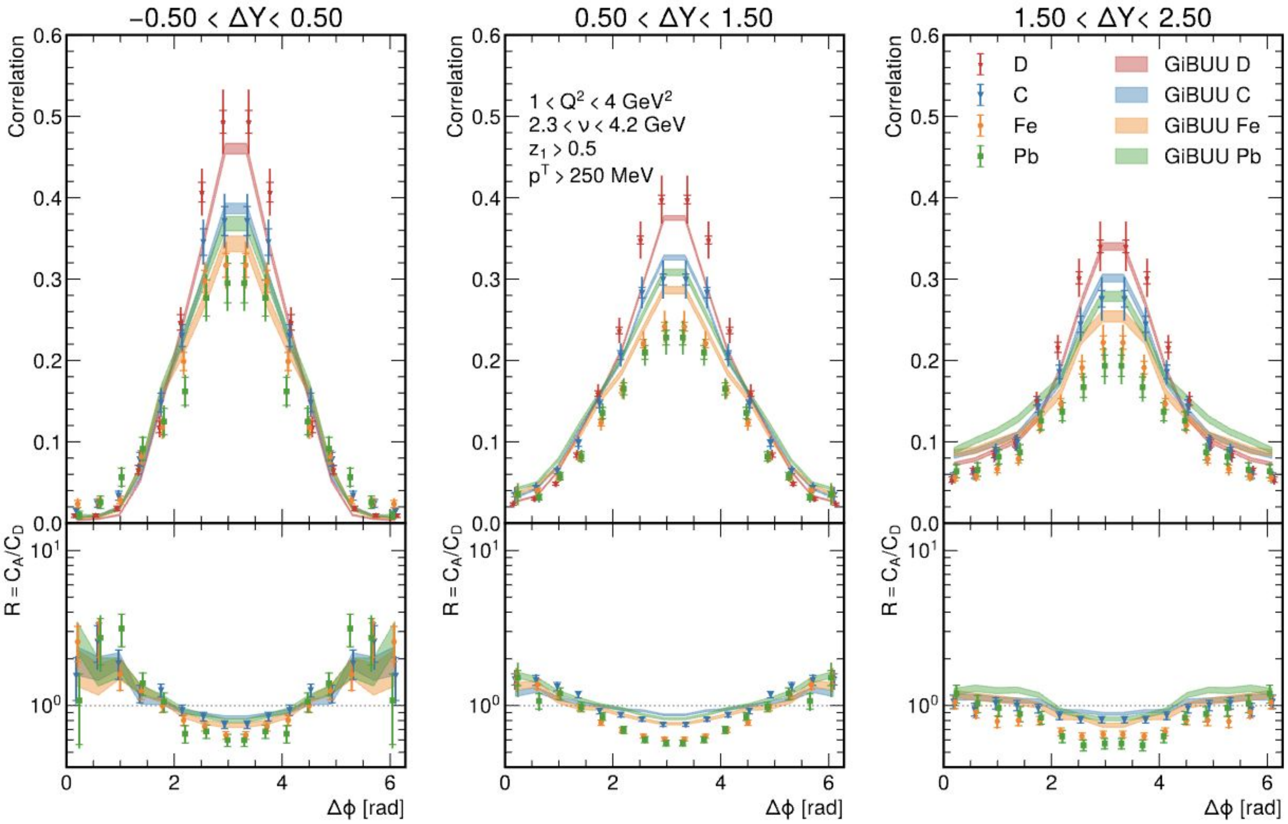
BROOKHAVEN NATIONAL LABORATORY

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

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

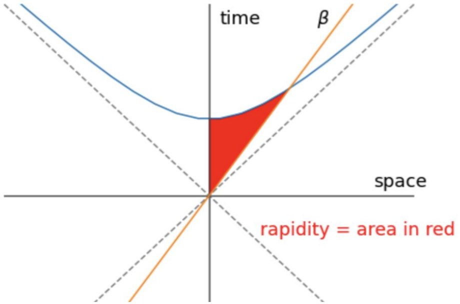


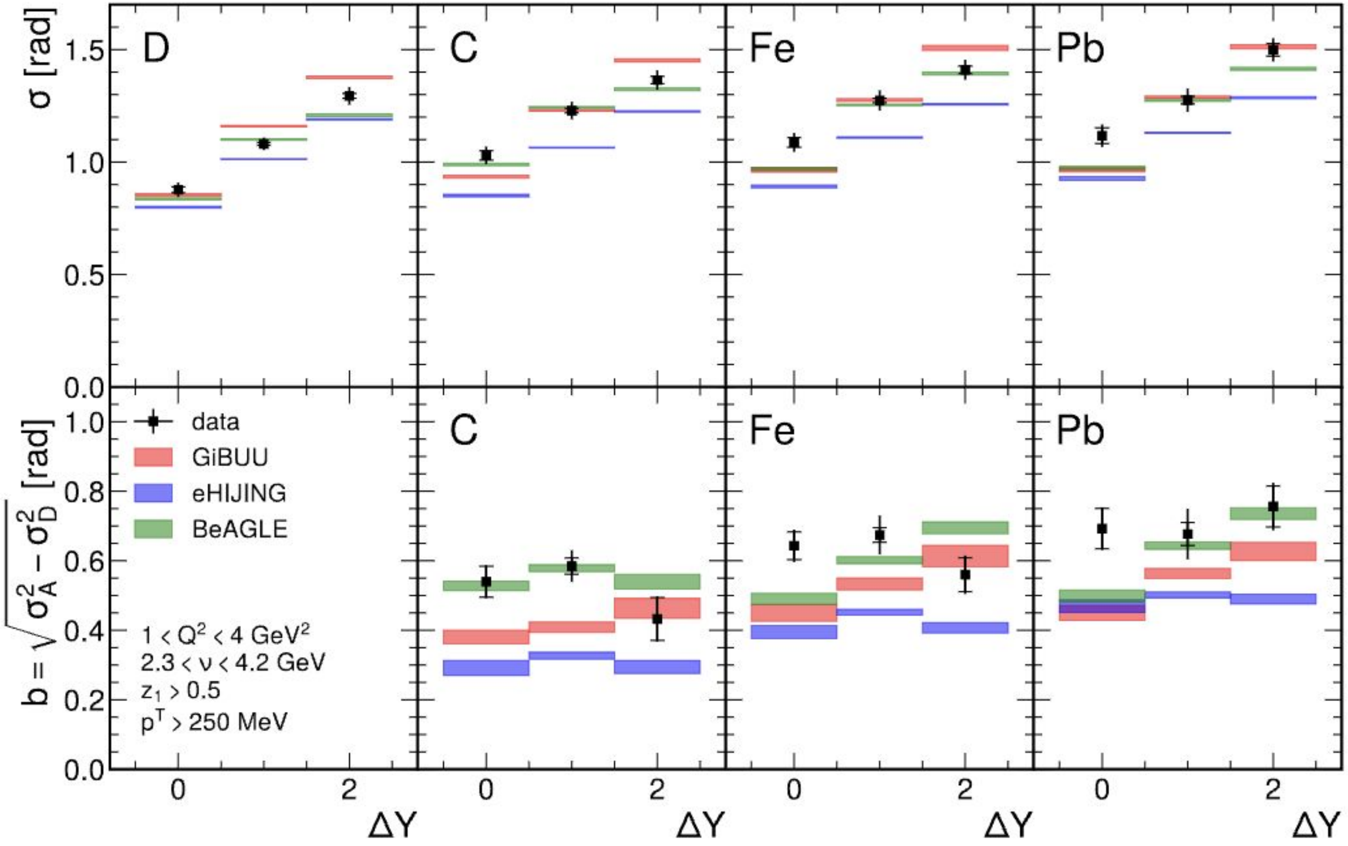


Multidimensional measurements

- Widths and broadenin can also be evaluated these bins

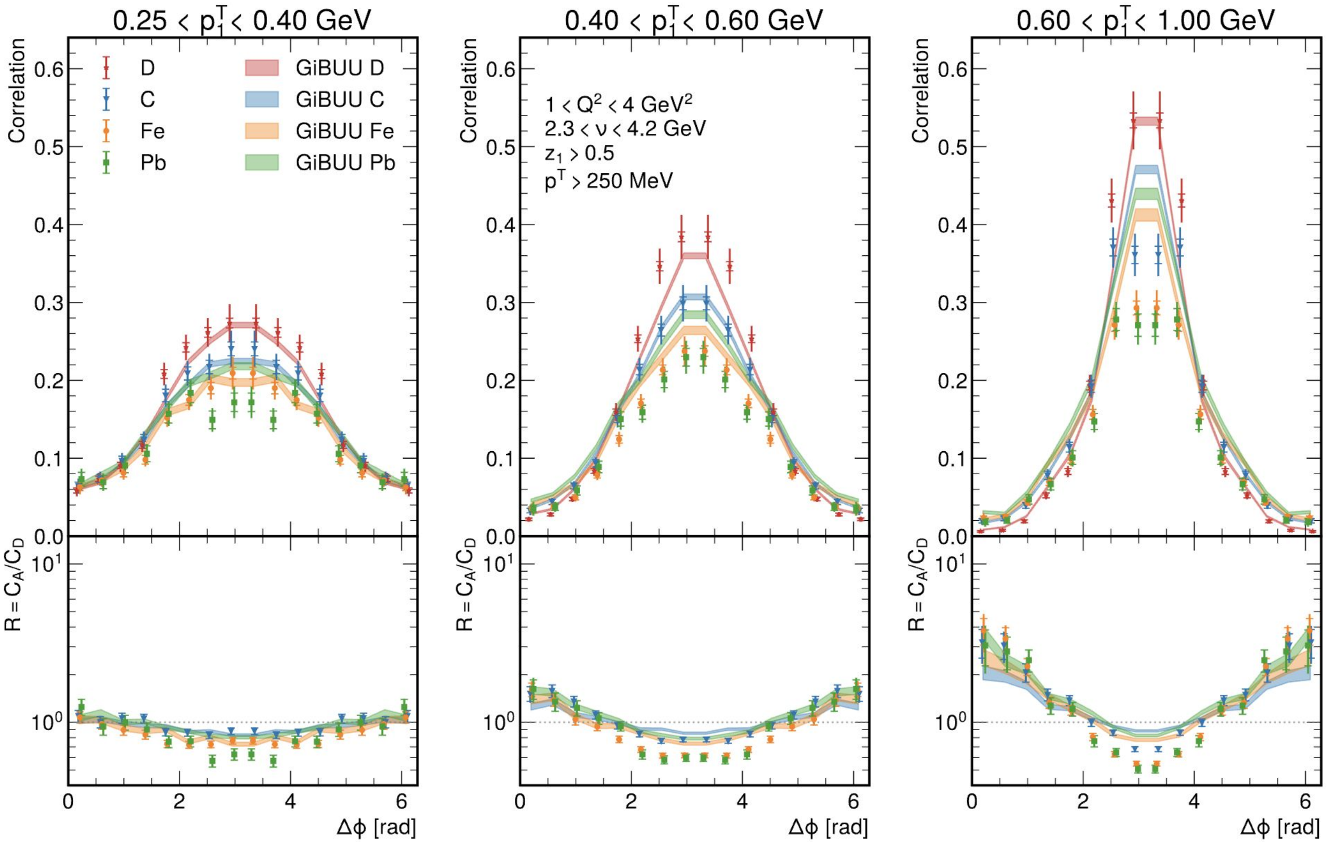
$$Y = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$

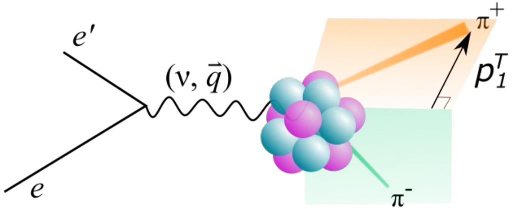




Multidimensional measurements

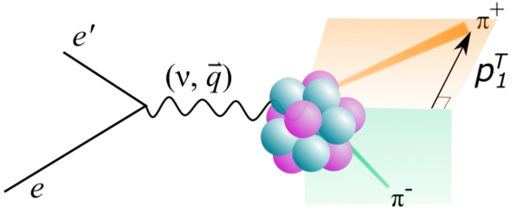
- Correlation functions get narrower as p_1^T gets larger

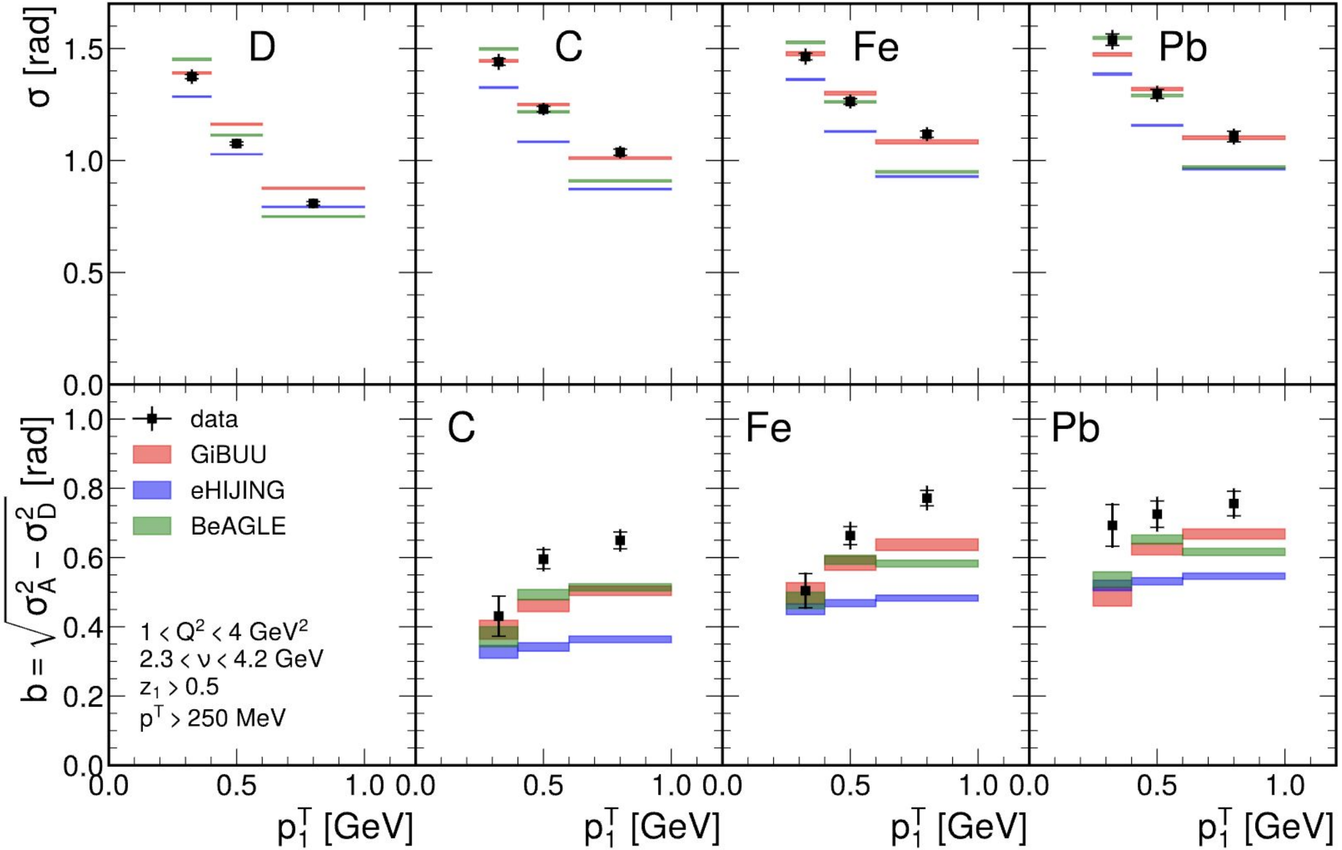




Multidimensional measurements

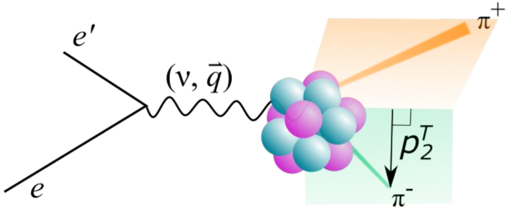
- Correlation functions get narrower as p_1^T gets larger
- And this is reflected in the widths

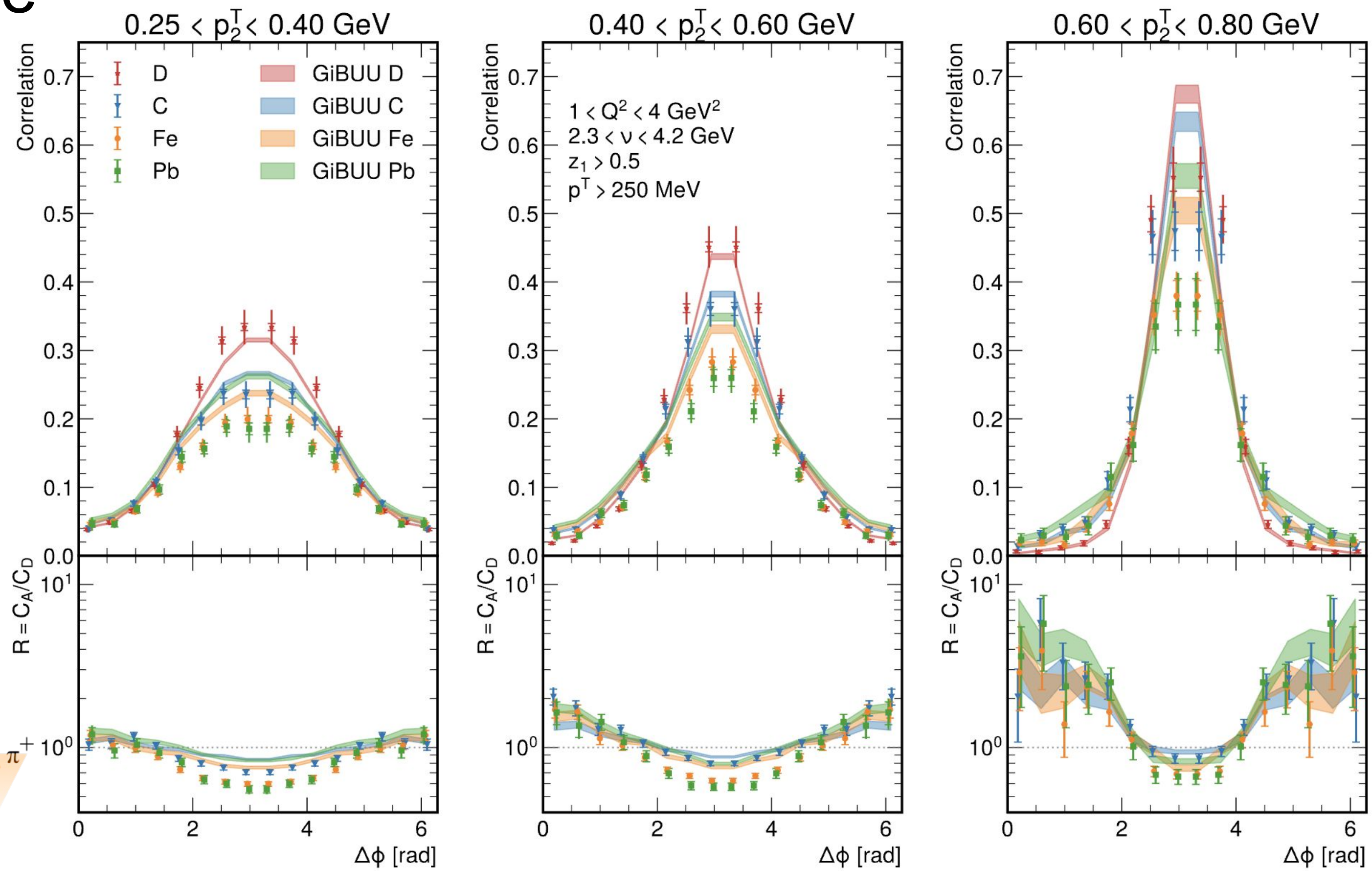




p_2^T dependence

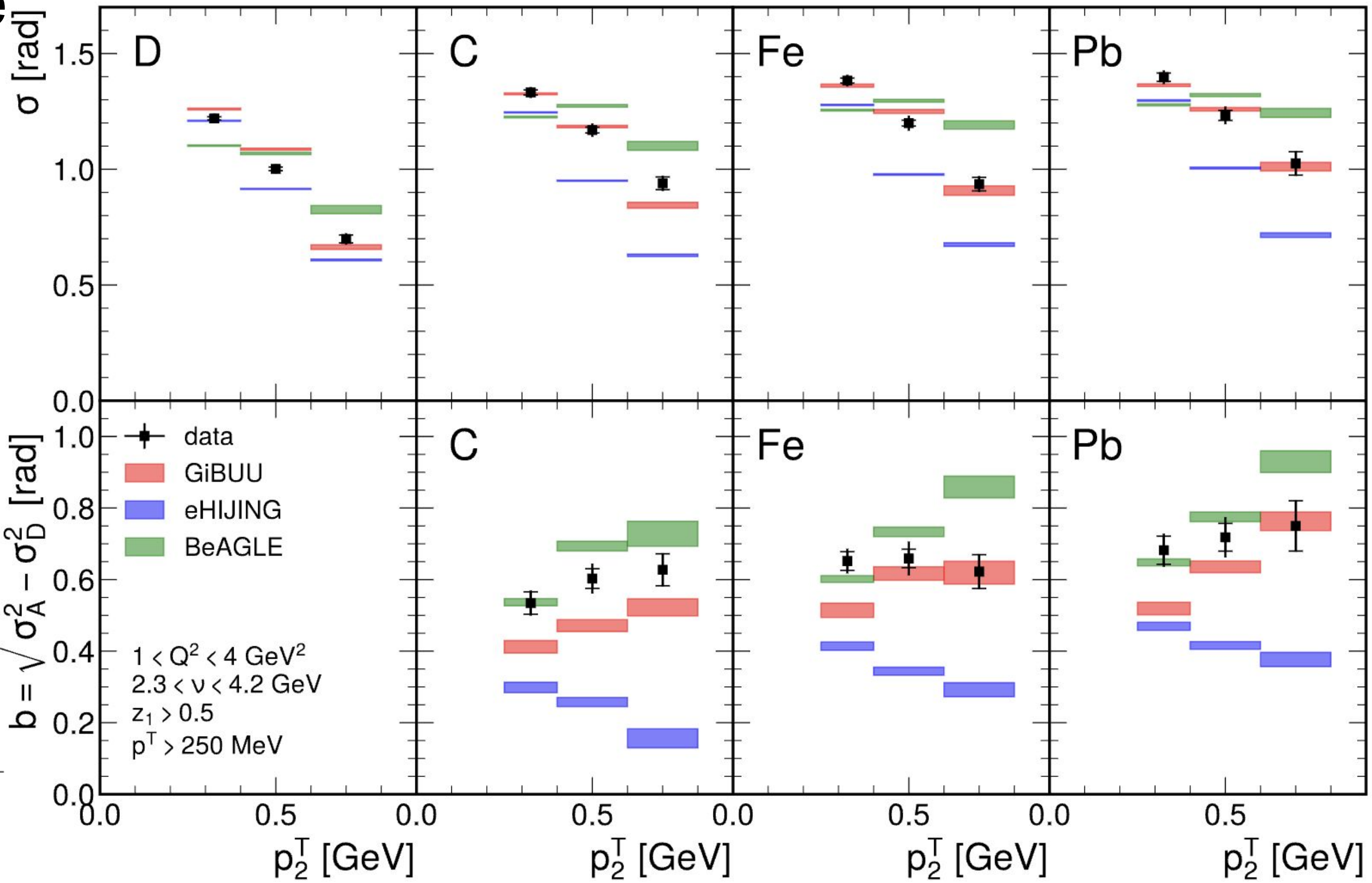
- Similar trend to the p_1^T dependence

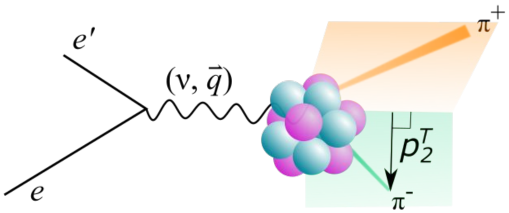




p_2^T dependence

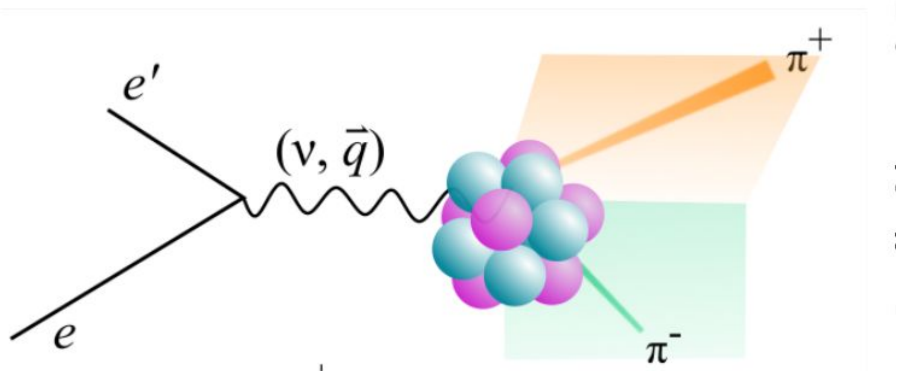
- Models predict different trends in the broadening vs p_2^T, which demonstrates the discriminating power of these measurements





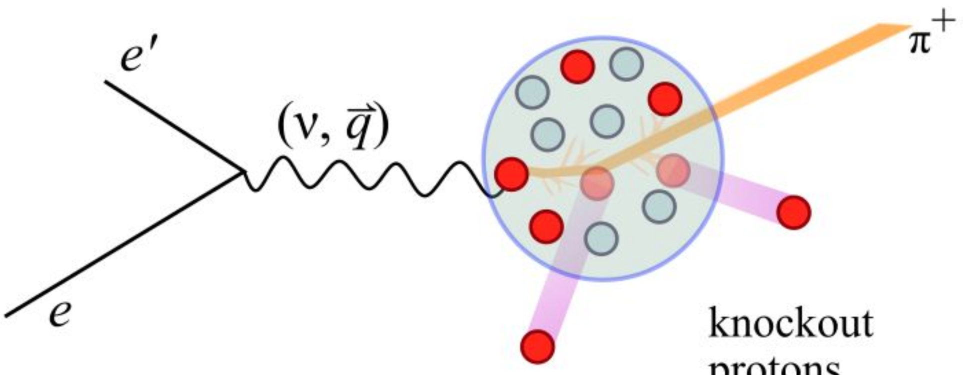
Di-Pion Event Selection

- 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+Cerenkov (P>2.7 GeV)
- Sub-leading π-
  - TOF cuts for identification
  - P>350 MeV
- Both hadrons:
  - pT>250 MeV



Pion-Proton Event selection

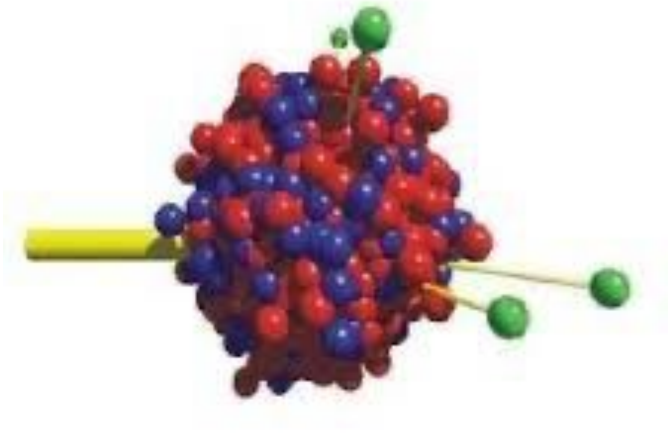
- Electron with DIS kinematics
  - $Q^2>1$ GeV^2
  - W>2 GeV
  - 2.3<ν<4.2 GeV
- Leading π+
  - $z=E_h/\nu>0.5$
  - Identified with
    - TOF only (P<2.7 GeV)
    - TOF+Cerenkov (P>2.7 GeV)
- Proton
  - TOF cuts
  - 0.2<P<2.8 GeV
- Both hadrons:
  - pT>70 MeV



Event Generators

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



eHIJING model

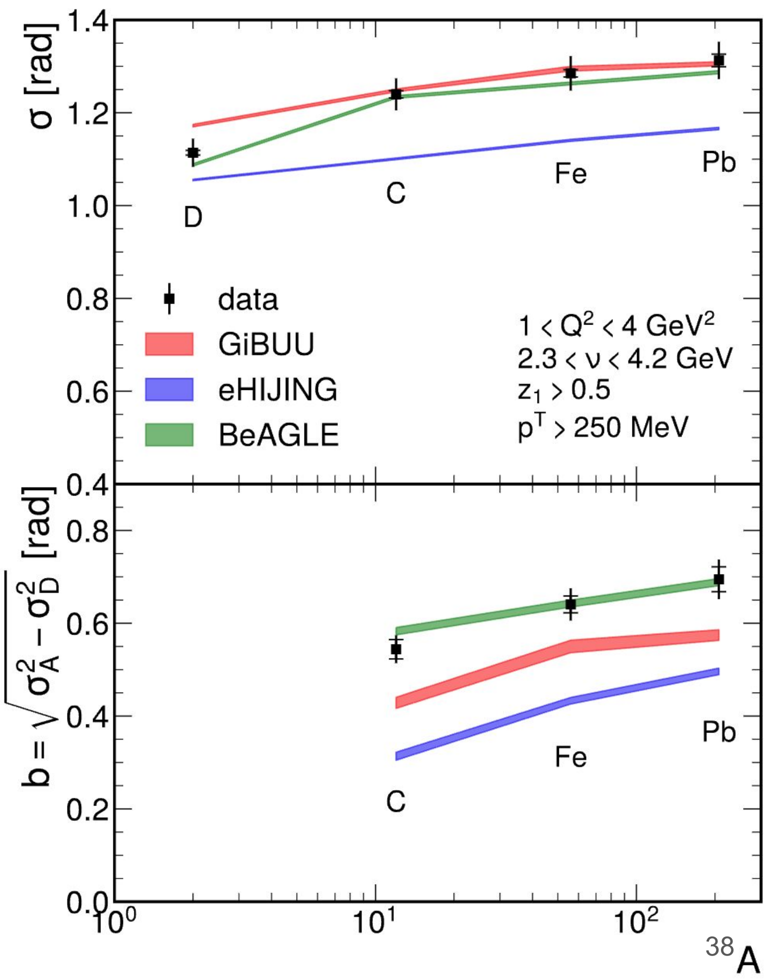
- Built on Pythia 8
- Interaction between hadrons and the nuclear medium proportional to the nuclear TMD PDF of gluons.

BeAGLE model

- 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)

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

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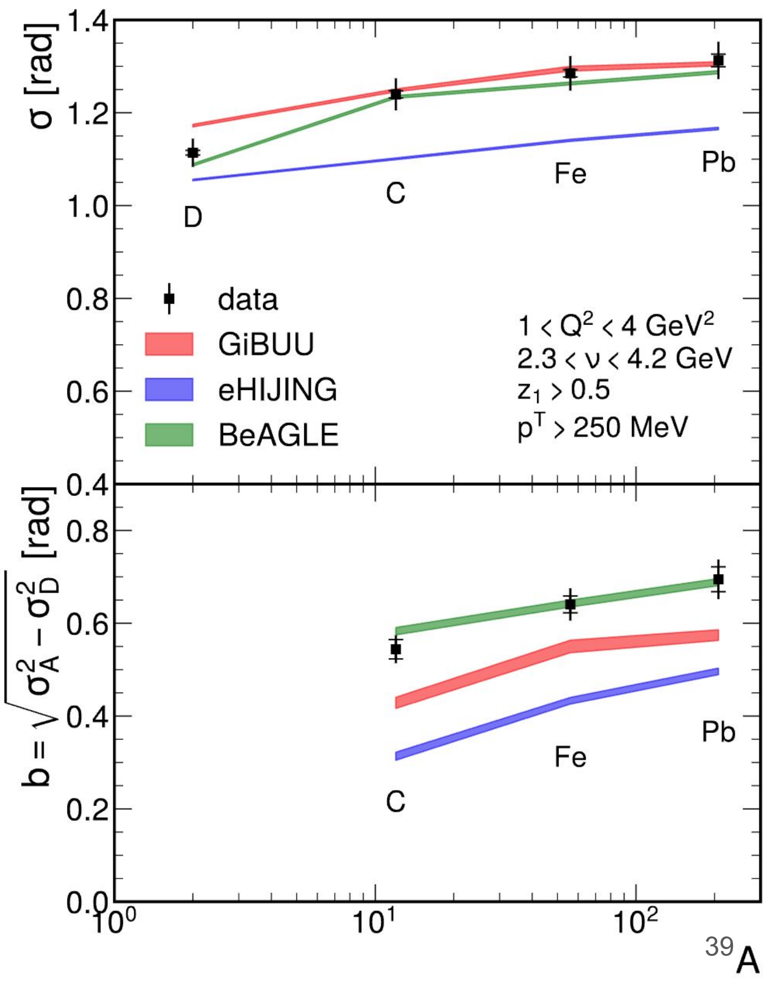
    - Interaction between hadrons and the nuclear medium proportional to the nuclear TMD PDF of gluons.



arXiv:2304.10779

Models

- BeAGLE
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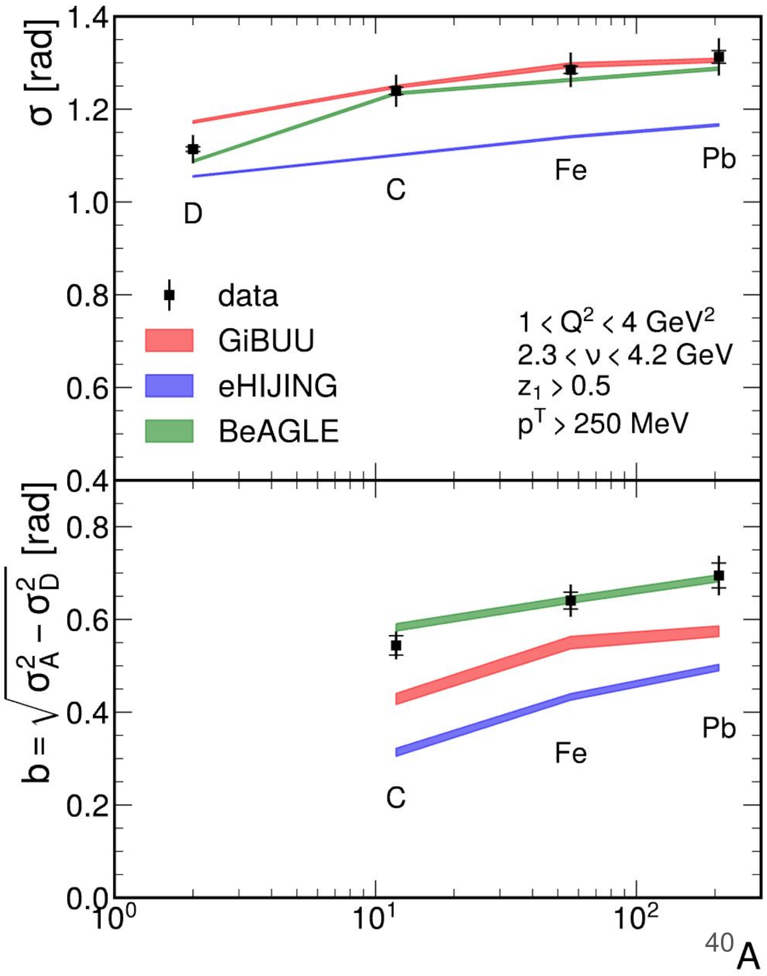

https://doi.org/10.1103/PhysRevD.106.012007