# Di-Hadron Correlations in Nuclei

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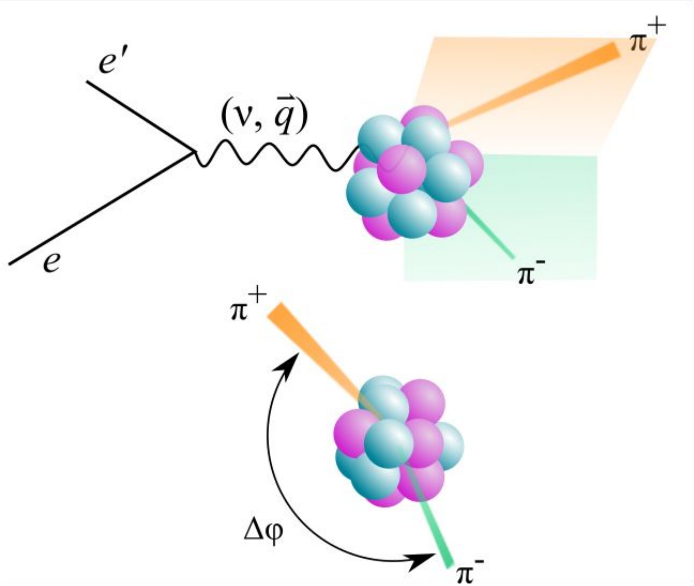
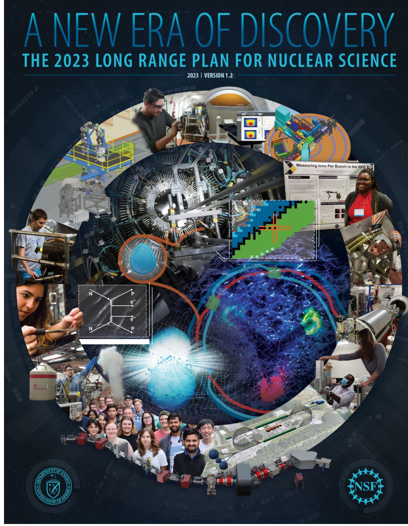
6/26/2024

UC RIVERSIDE

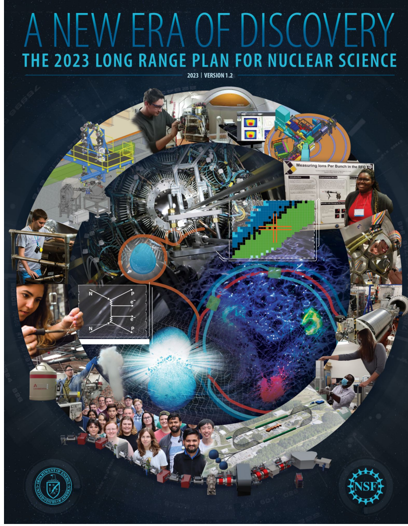
clas
CEBAF Large Acceptance Spectrometer

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

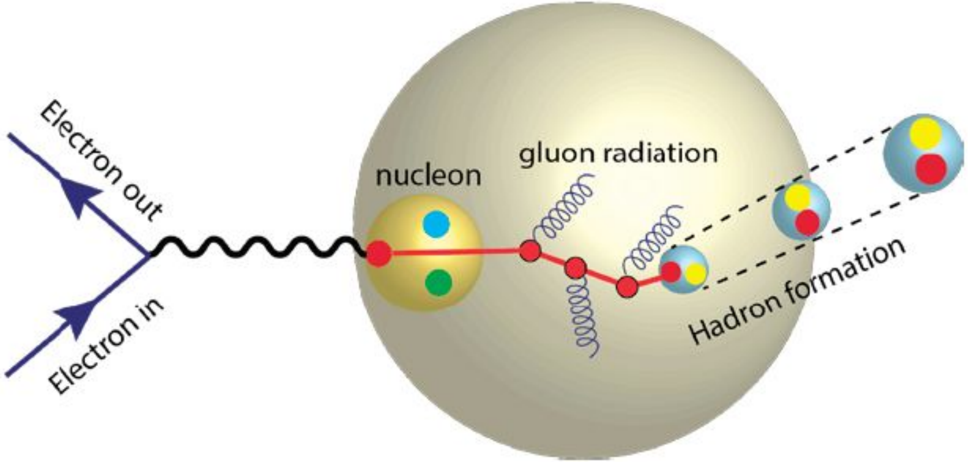


… and how does hadronization change in a dense partonic environment?




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



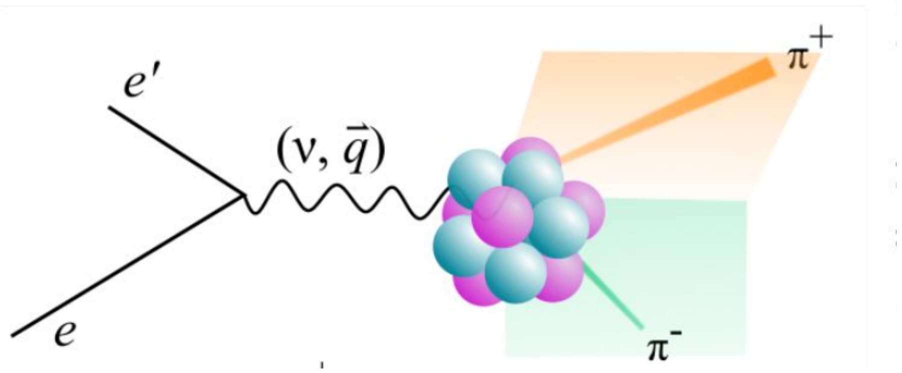
# Event topologies

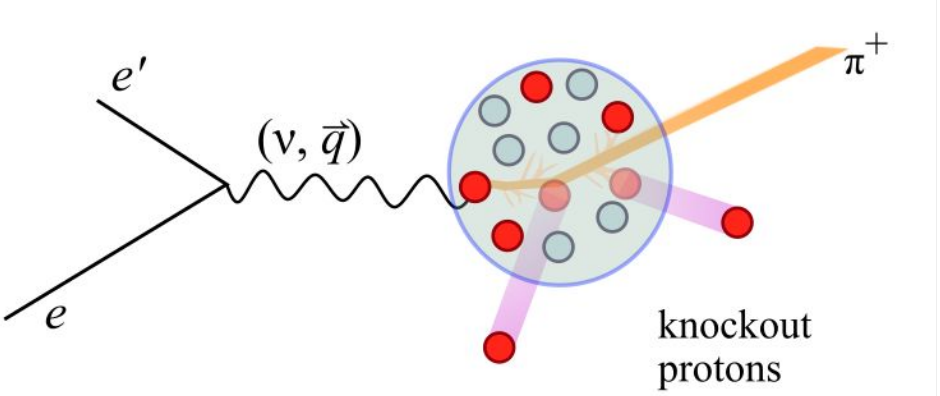
Di-pion:

- High energy π+ and low energy π-

Pion+proton

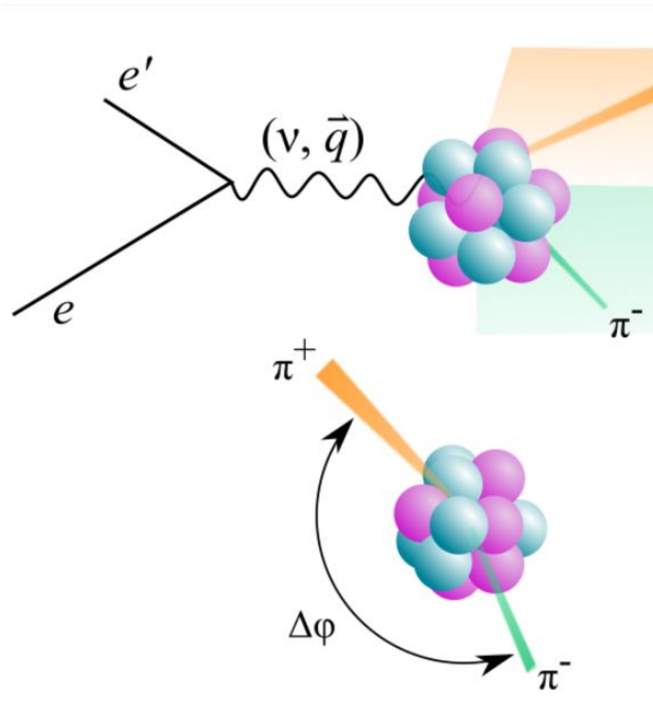
- High energy π+ and knocked-out proton



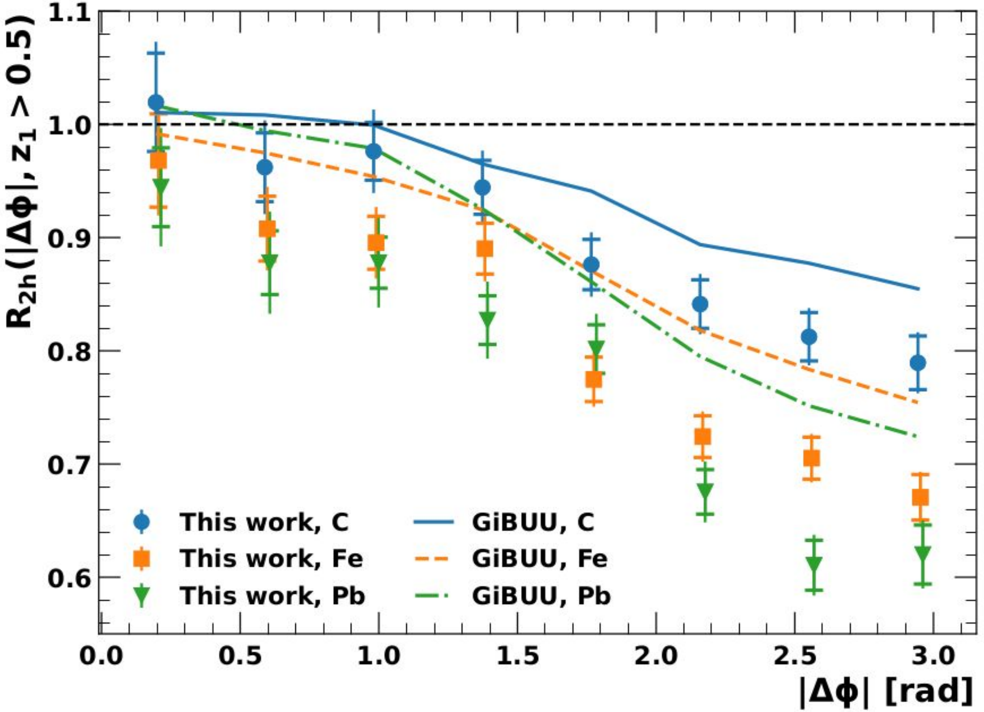



Earlier results …

# 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 ?*

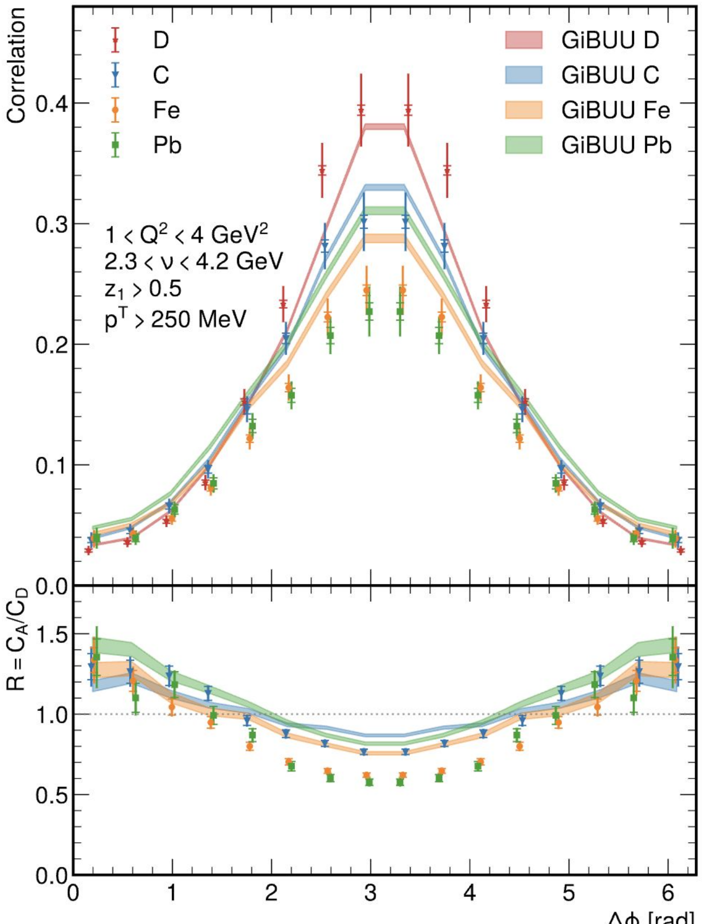
# Our observable: correlation function

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

- $N_{eh}$ 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

Leading $\pi^+$, subleading $\pi^-$

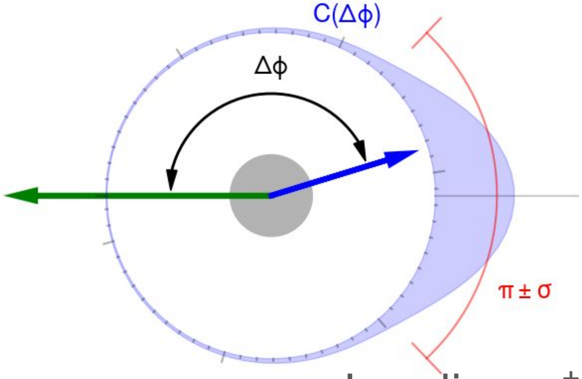


# Derived quantities: RMS widths and broadenings

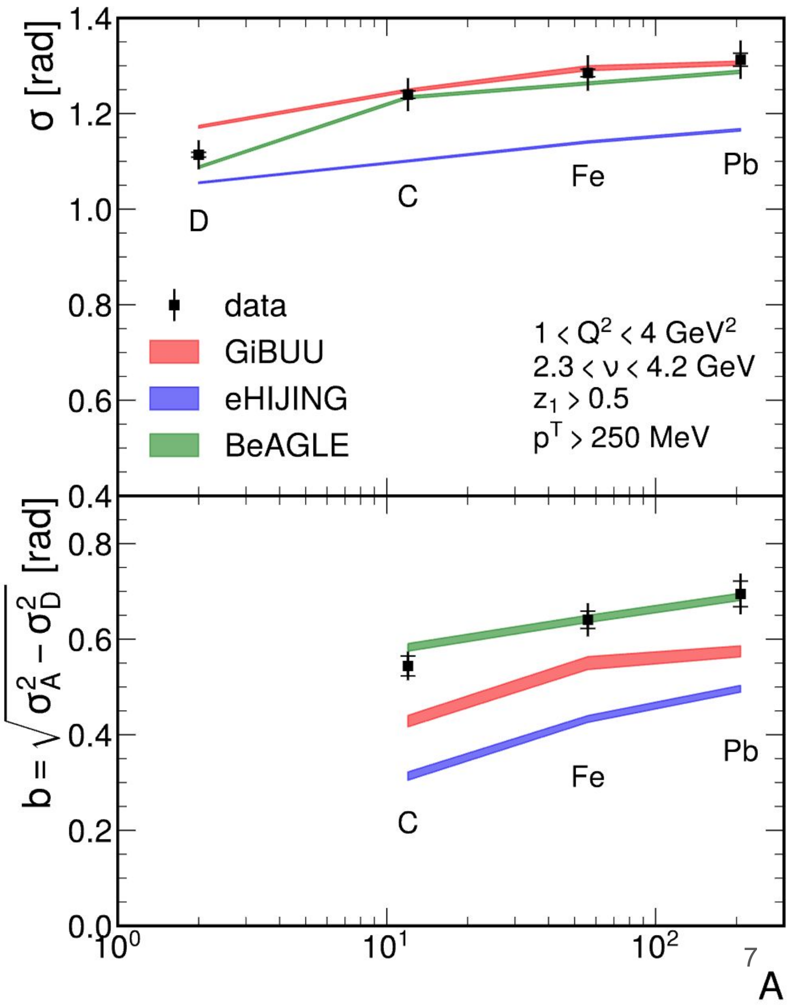
RMS width:

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

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

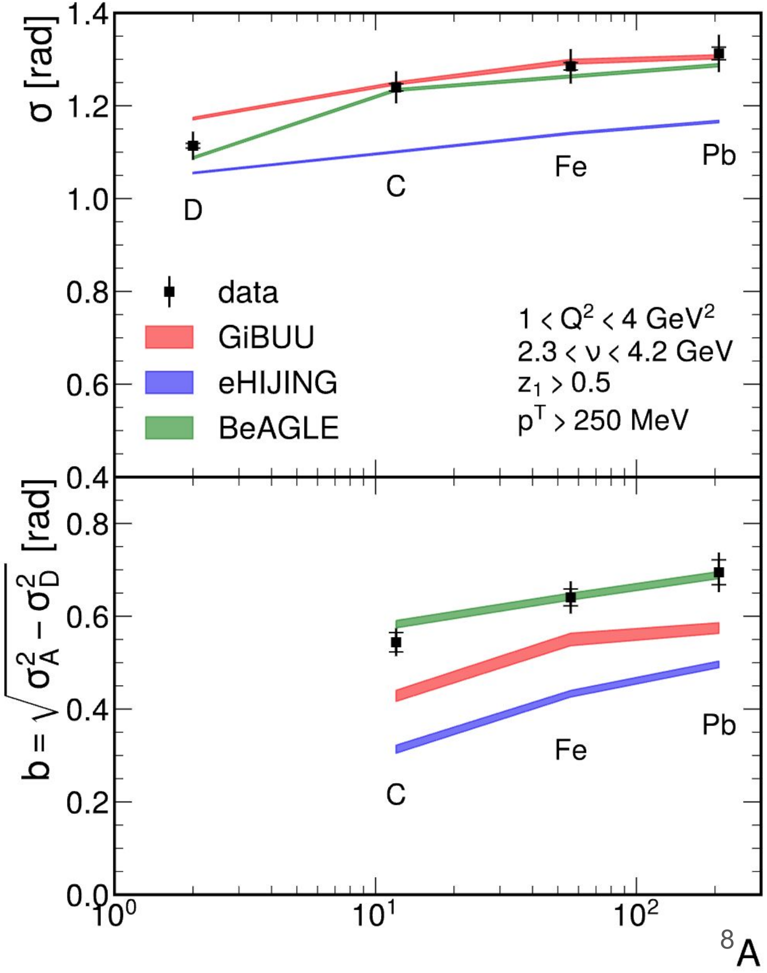



Leading $\pi^+$, subleading $\pi^-$



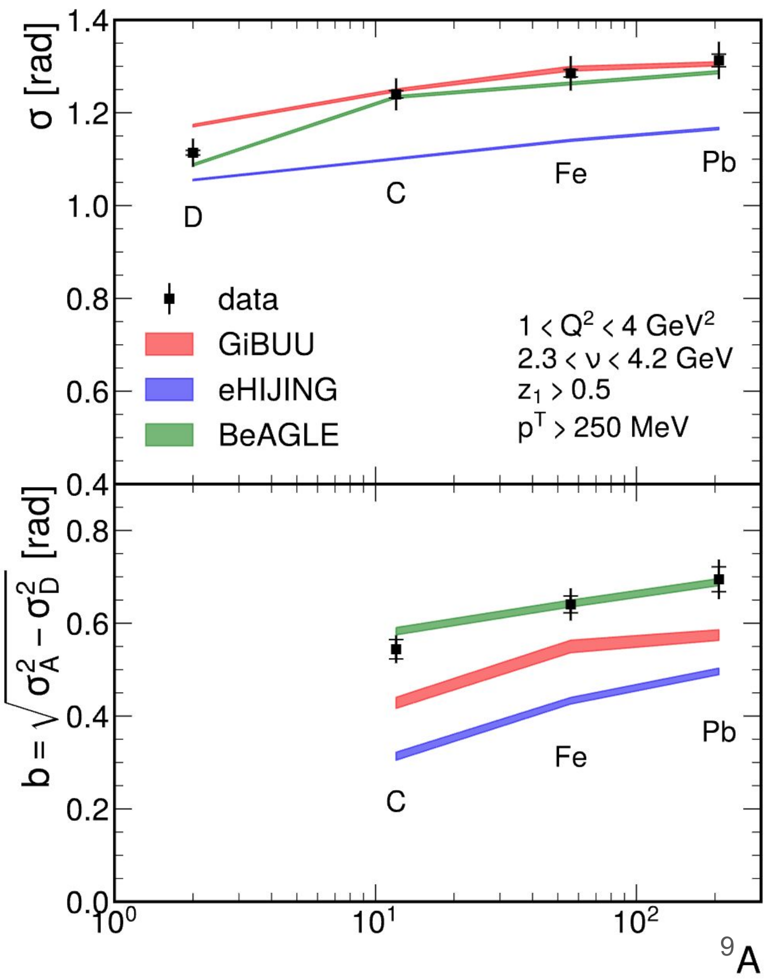
# Derived quantities: RMS widths and broadenings

- 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



# Models

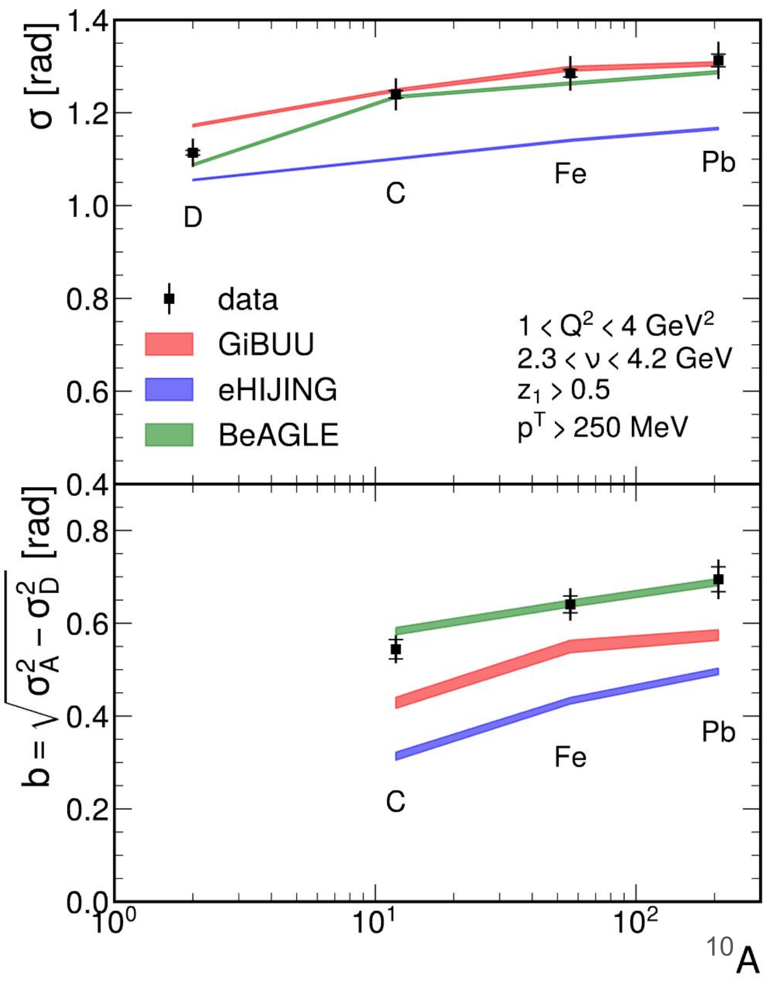
- GiBUU
  - Final-state interactions
  - Absorption
  - Hadron production mechanisms
  - Pre-hadron degrees of freedom
  - Color transparency
  - Nuclear shadowing




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

# Models

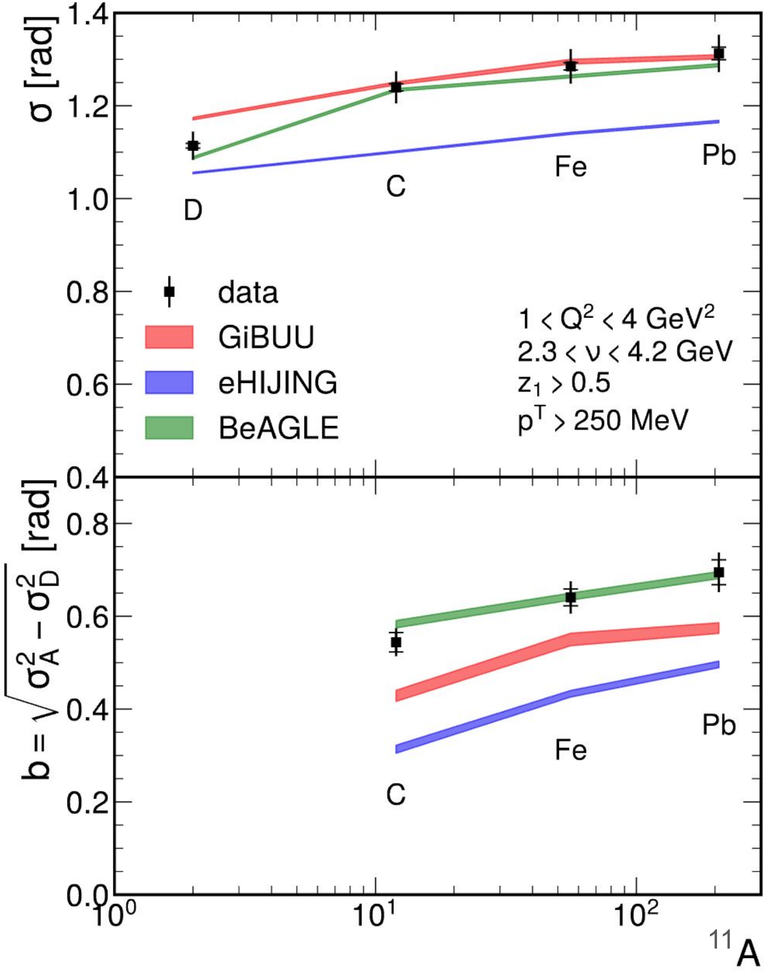
- eHIJING
    - Based on Pythia8
    - Interaction between hadrons and the nuclear medium proportional to the nuclear TMD PDF of gluons.




arXiv:2304.10779

# Models

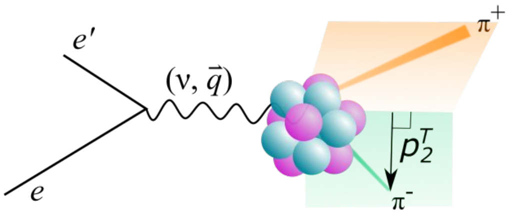
- BeAGLE
    - Mixture of components from multiple generators
        - Primary interaction (Pythia6)
        - Nuclear remnant decay/de-excitation (FLUKA)
        - Intranuclear cascade (DPMJet)
        - Geometric density of nucleons (PyQM)
        - Nuclear parton distribution functions (LHAPDF5)

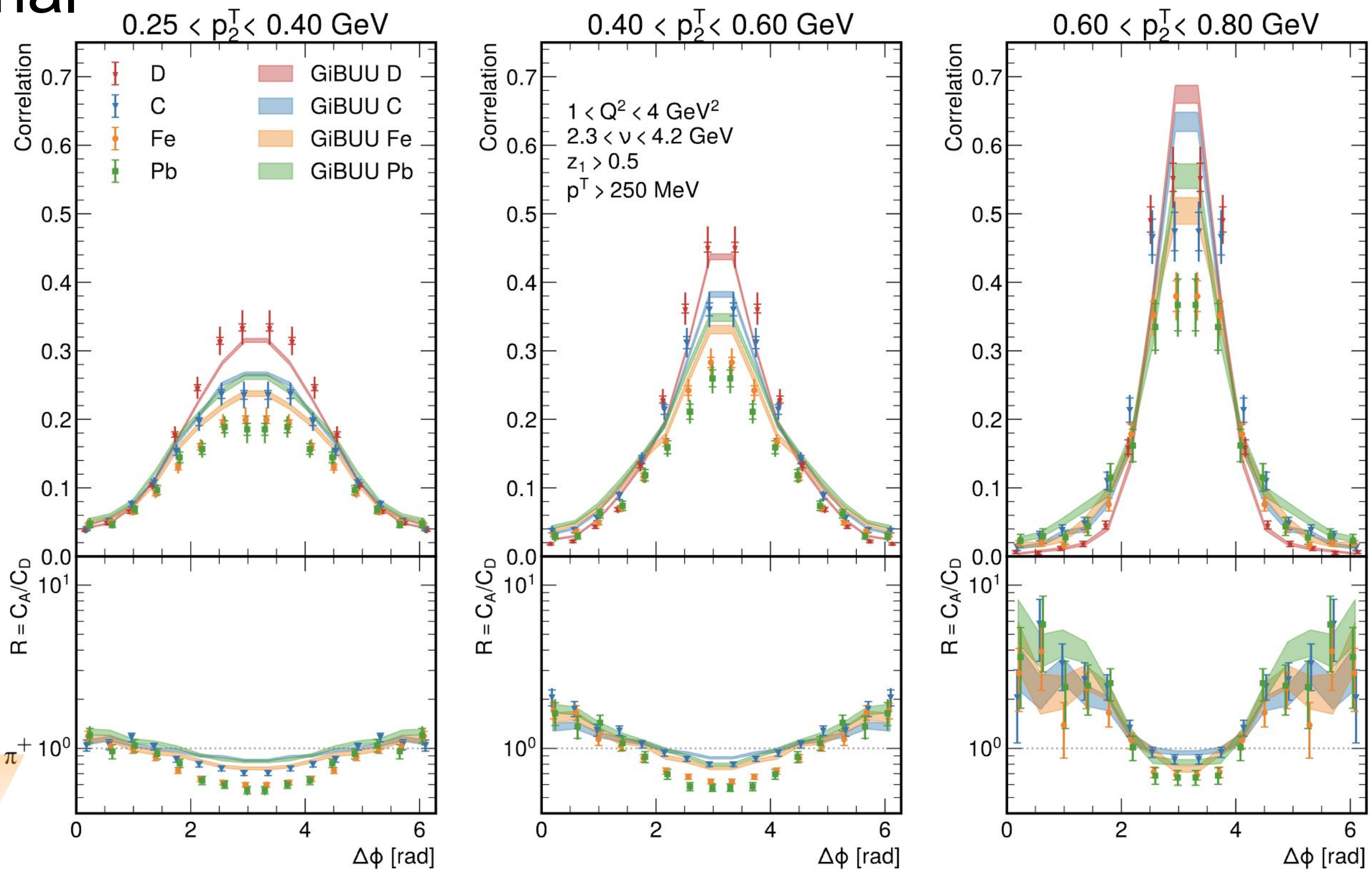



https://doi.org/10.1103/PhysRevD.106.012007

# Multi-dimensional measurements

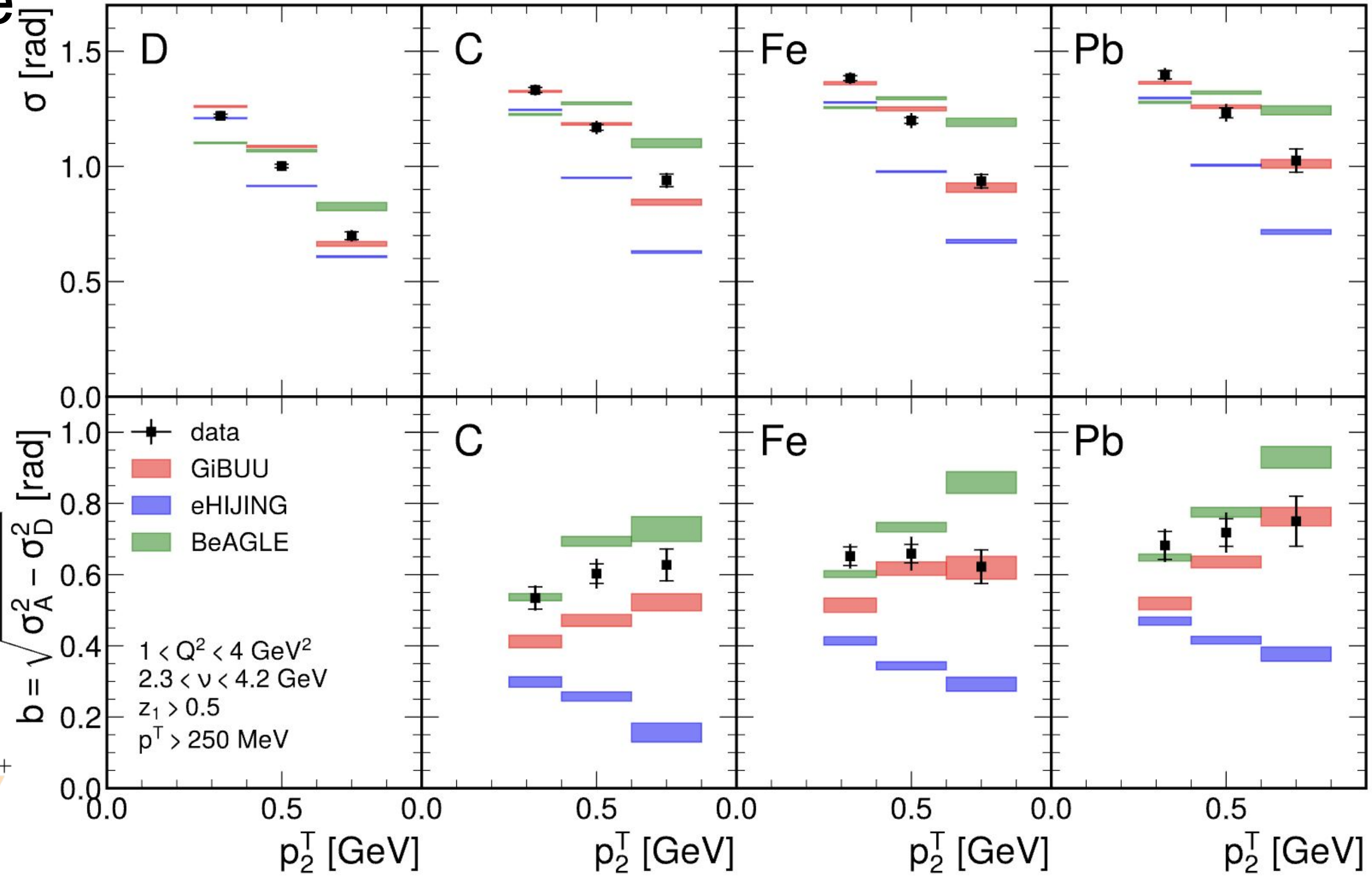
- At large $p^T_2$, the correlation function peak becomes more narrow
- Nuclear effects strongly depend on pT2

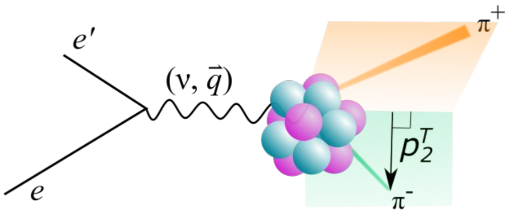


# $p_2{}^T$ dependence

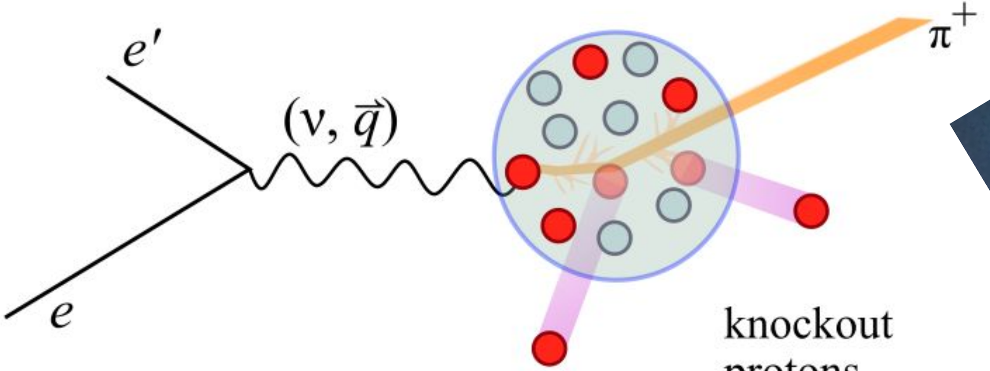
- Models predict different trends in the broadening vs $p_2{}^T$, which demonstrates the discriminating power of these measurements



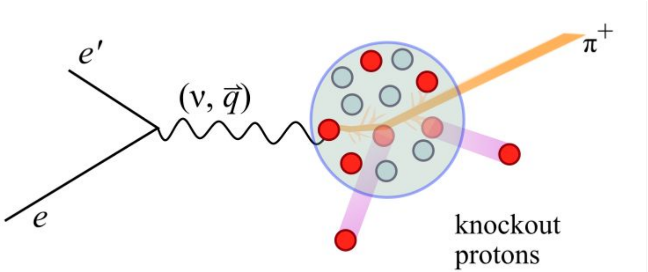
**How does the nucleus react to a fast quark**?

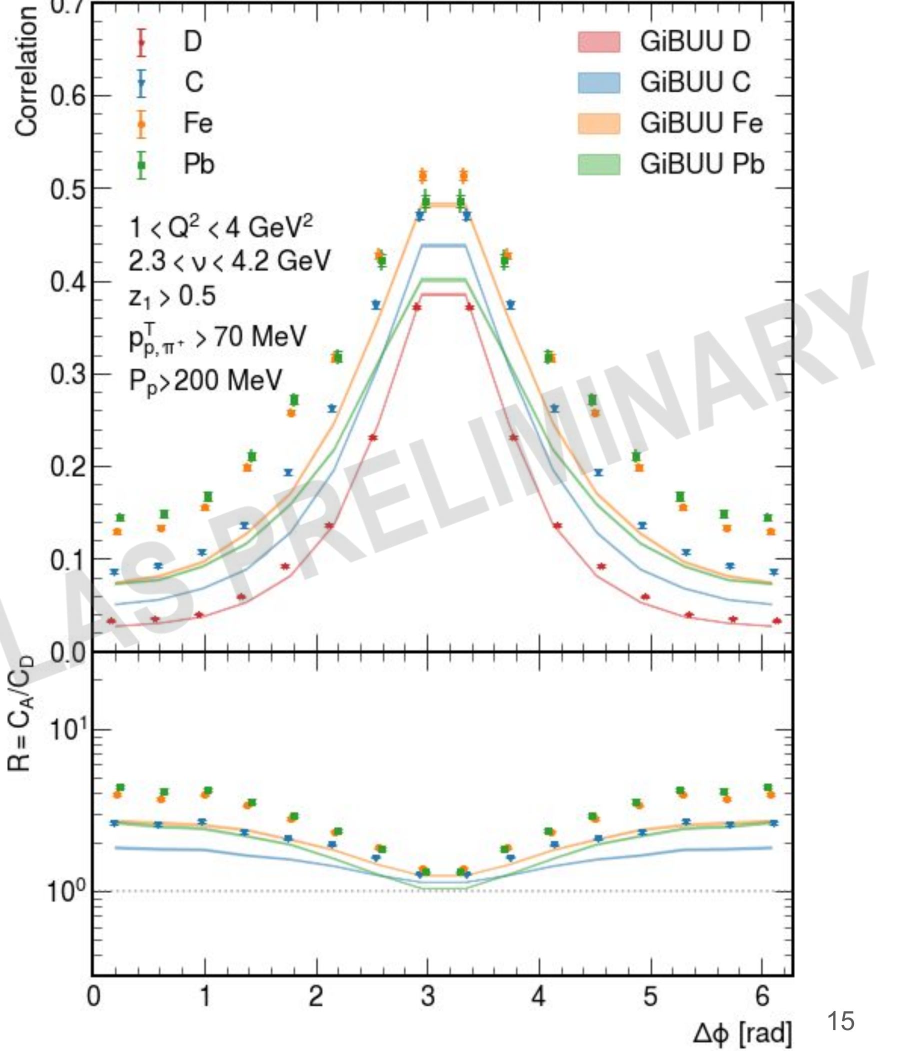
Protons proxy for “nuclear response”




# Results for the pion-proton analysis (NEW)

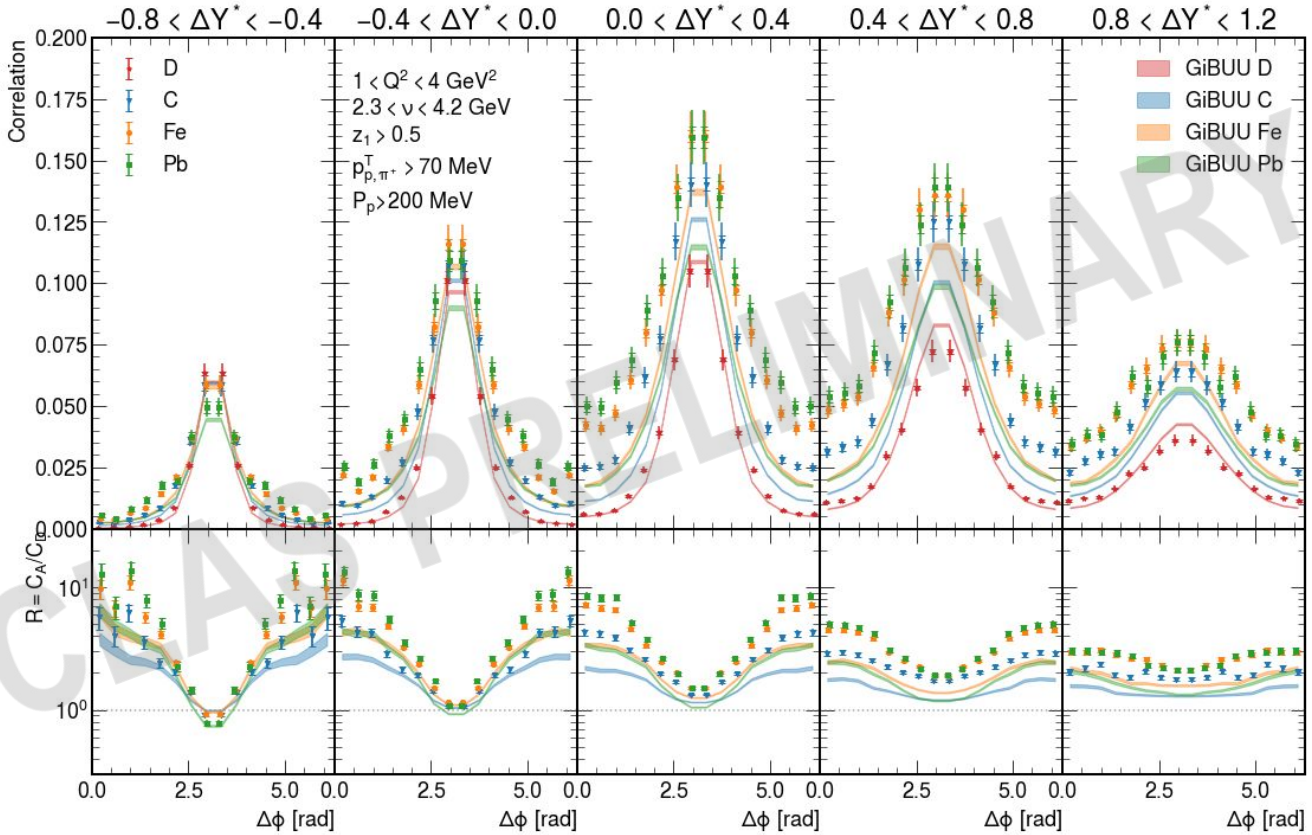
- Similar to di-pion analysis…,
  - Peak is at Δφ=π, wider correlation functions for nuclear than for deuterium
- But unlike di-pion case…
  - Taller peaks for nuclear than for deuterium…



# Multidimensional πp results:

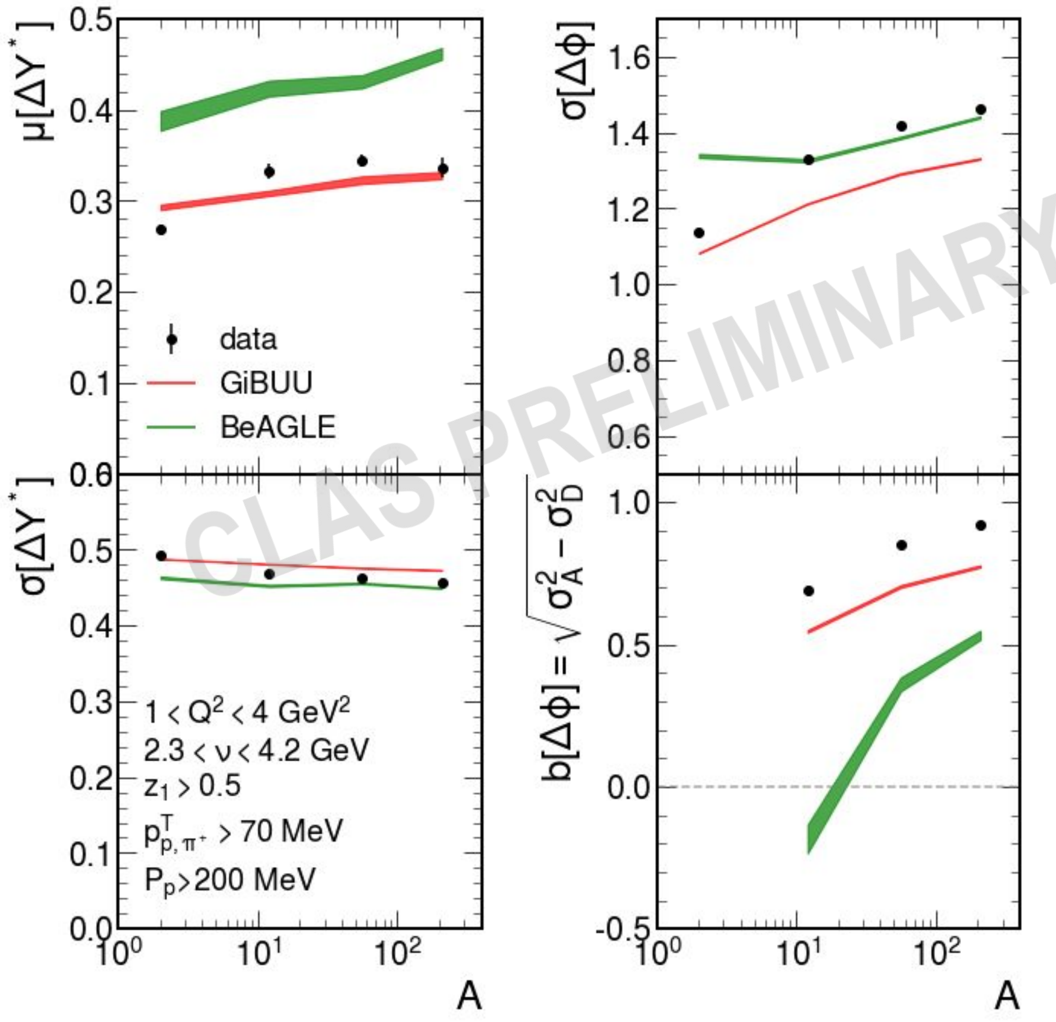
$$\Delta Y^* = Y_{\pi^+} - Y_p - (Y_{\rm cm} - Y_{\rm lab}) \qquad Y = \frac{1}{2}\ln\frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$




- Wider correlation functions for larger positive ΔY*
- Models qualitatively predicts this trend

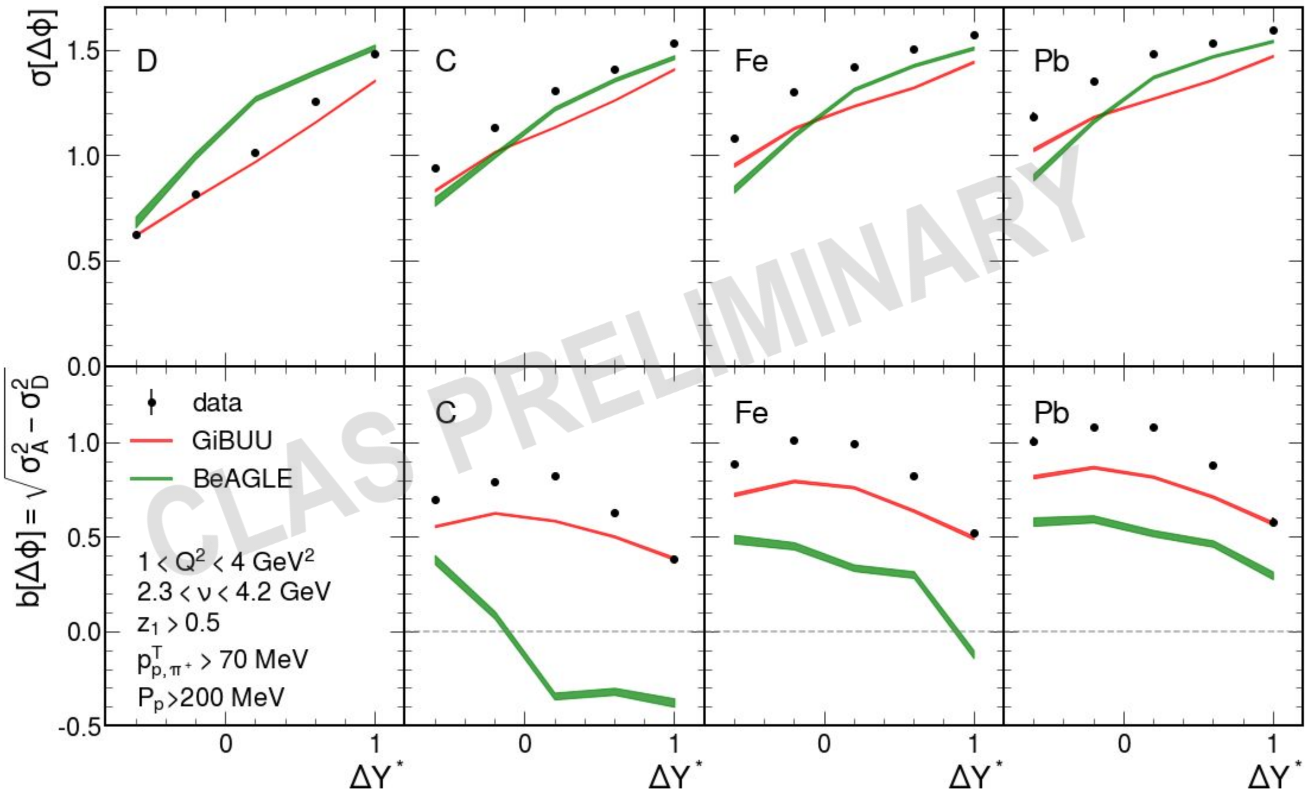
# Derived quantities Comparison of event generators

- Strong discrimination power for models.



# Azimuthal broadening as a function of ΔY*

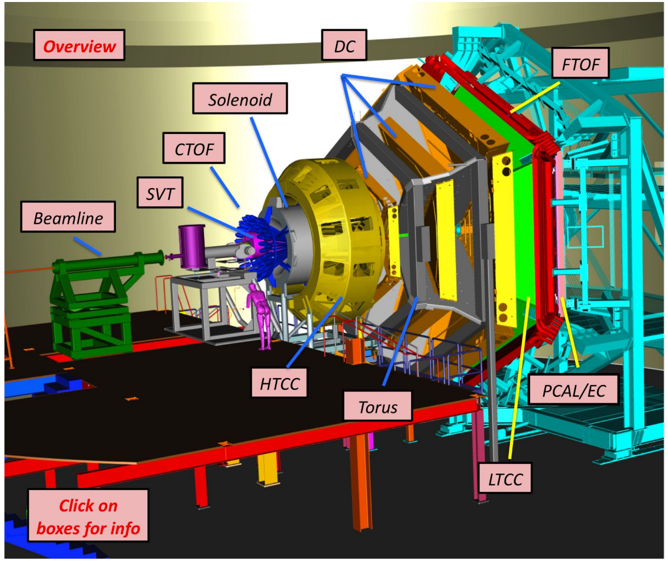
- σ[Δφ] increases a function of rapidity separation
- Both models predict this trend



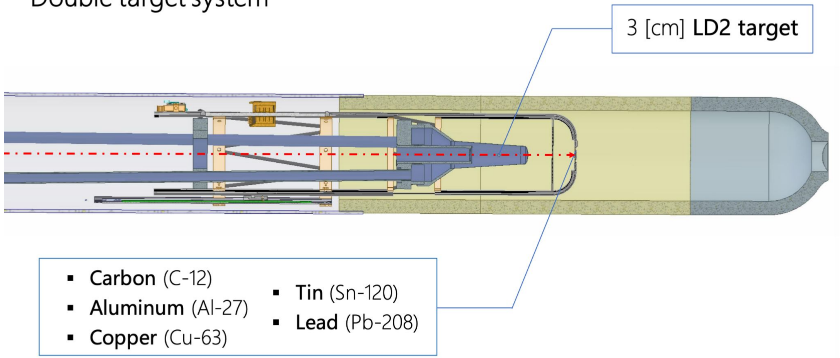
# Follow-up measurements with upgraded CLAS12 (Run Group E)

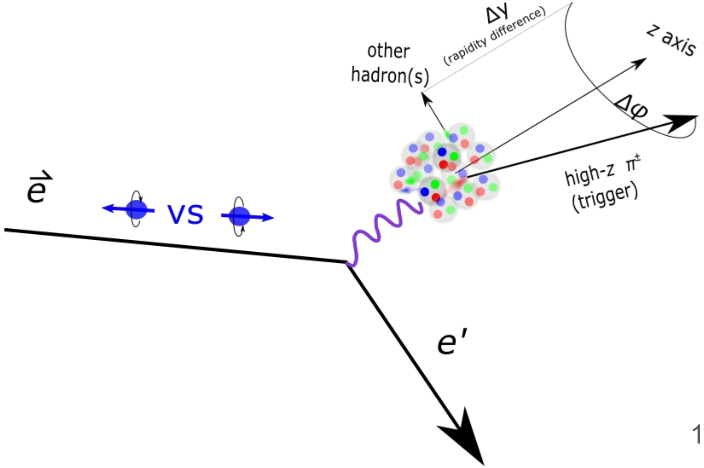
These di-hadron measurements can be extended using recent measurements with

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



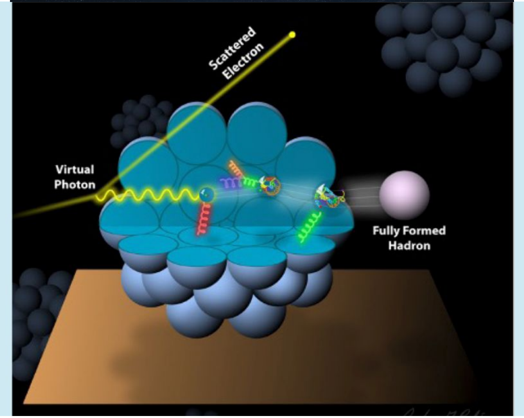

Double target system



# 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?

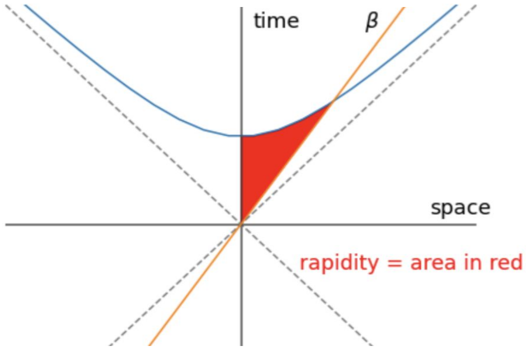



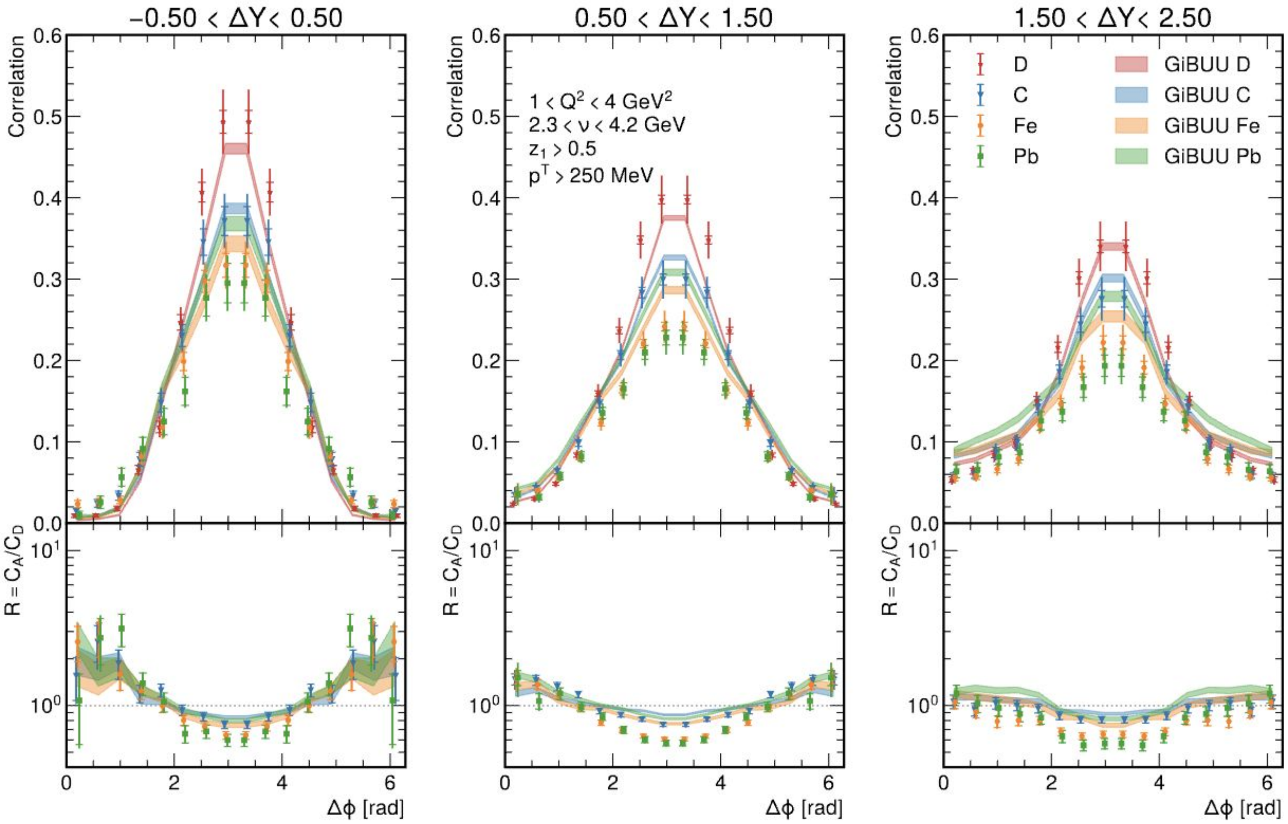
# Backup

# 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 $p_T^2$

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

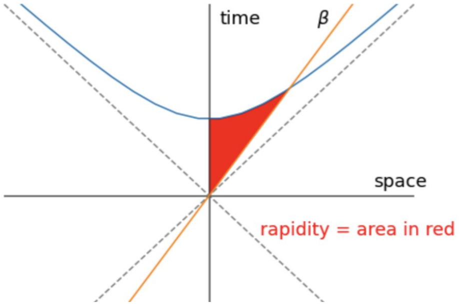


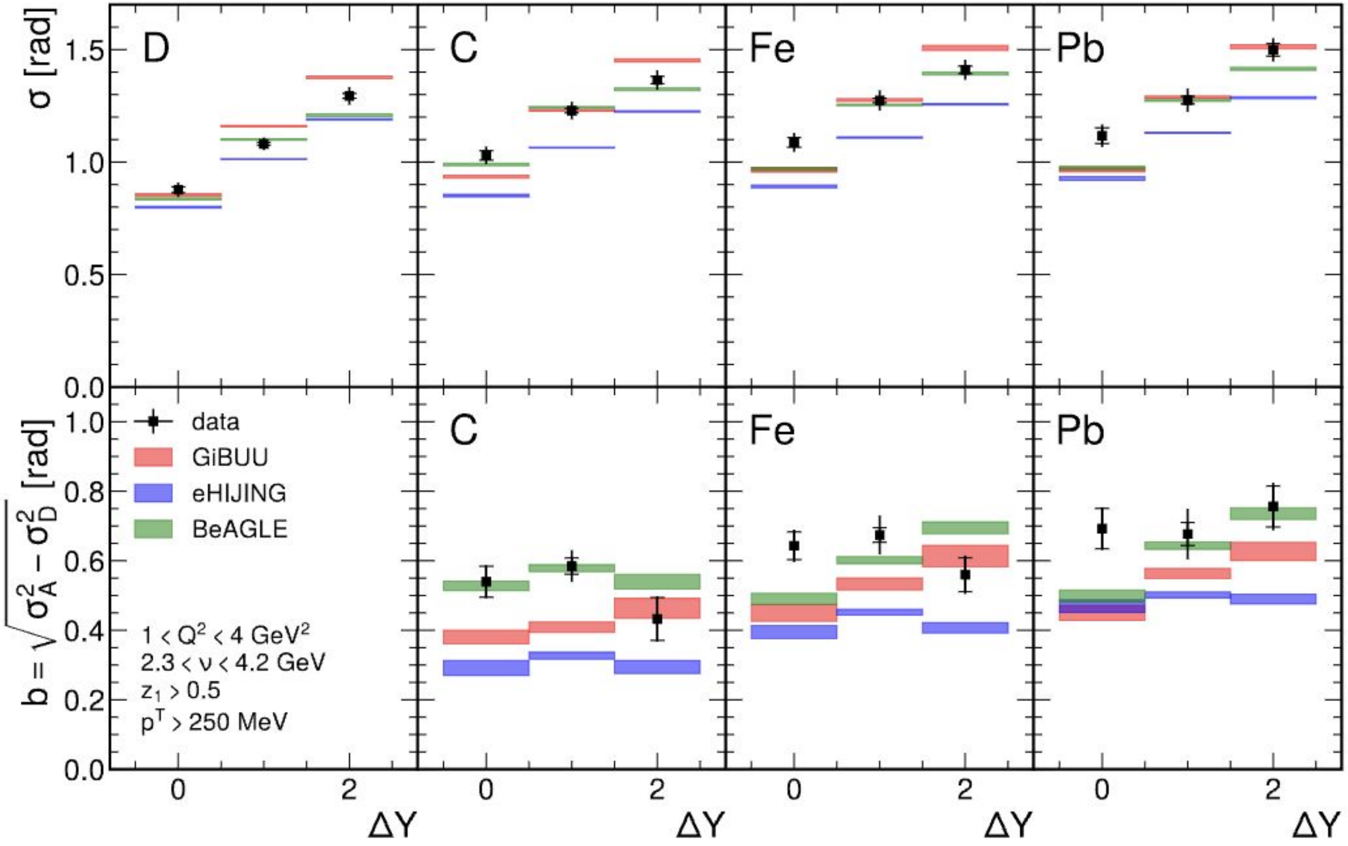



# Multidimensional measurements

- Widths and broadenin can also be evaluated these bins

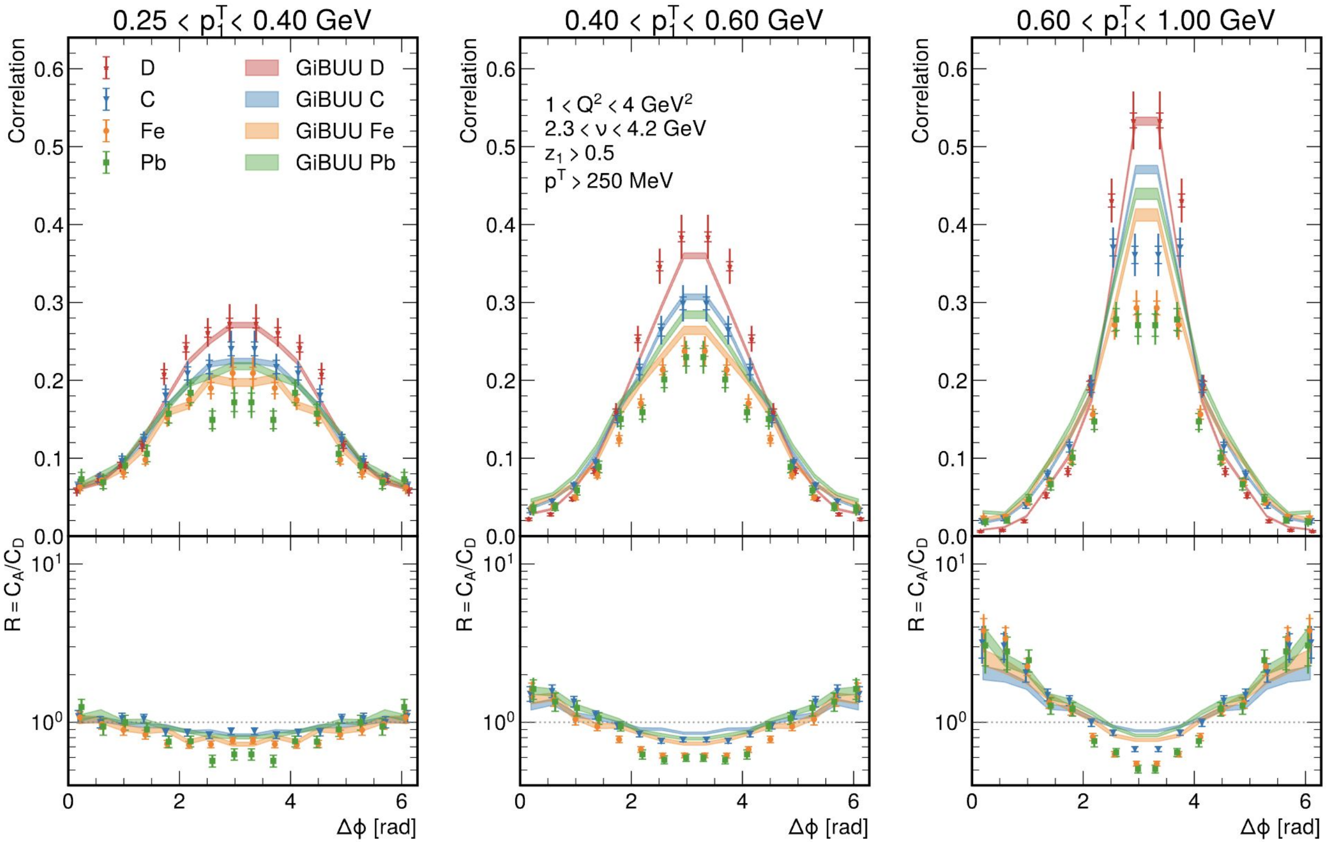
$$Y = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$

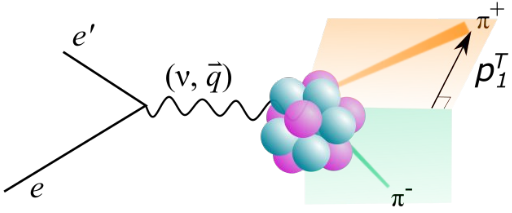


# Multidimensional measurements

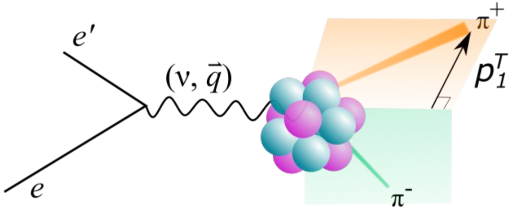
- Correlation functions get narrower as $p_1^T$ gets larger

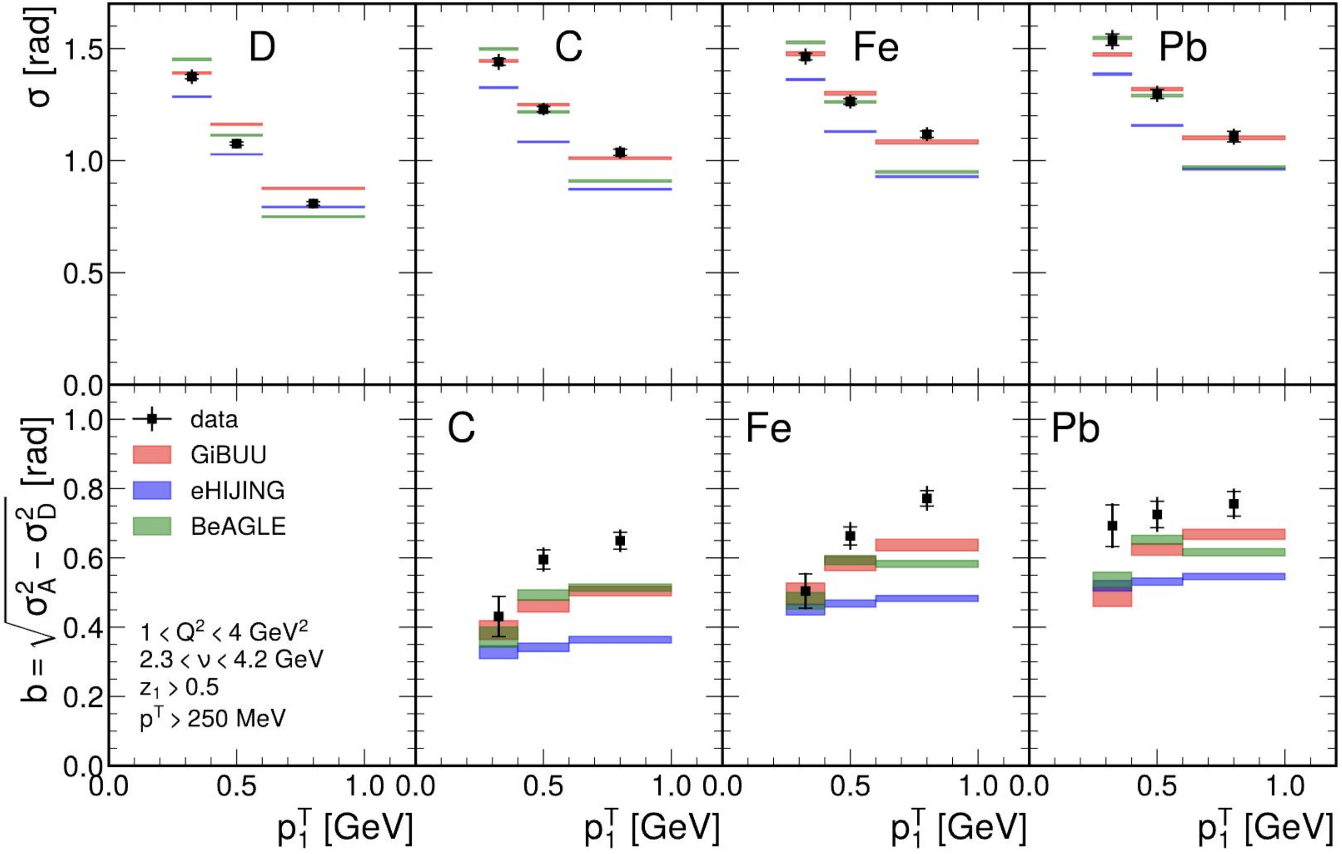


# Multidimensional measurements

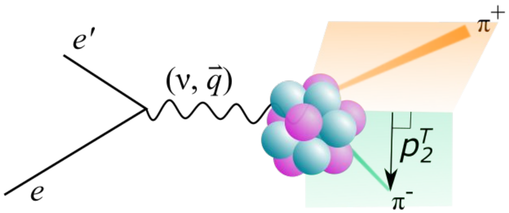
- Correlation functions get narrower as $p_1^T$ gets larger
- And this is reflected in the widths

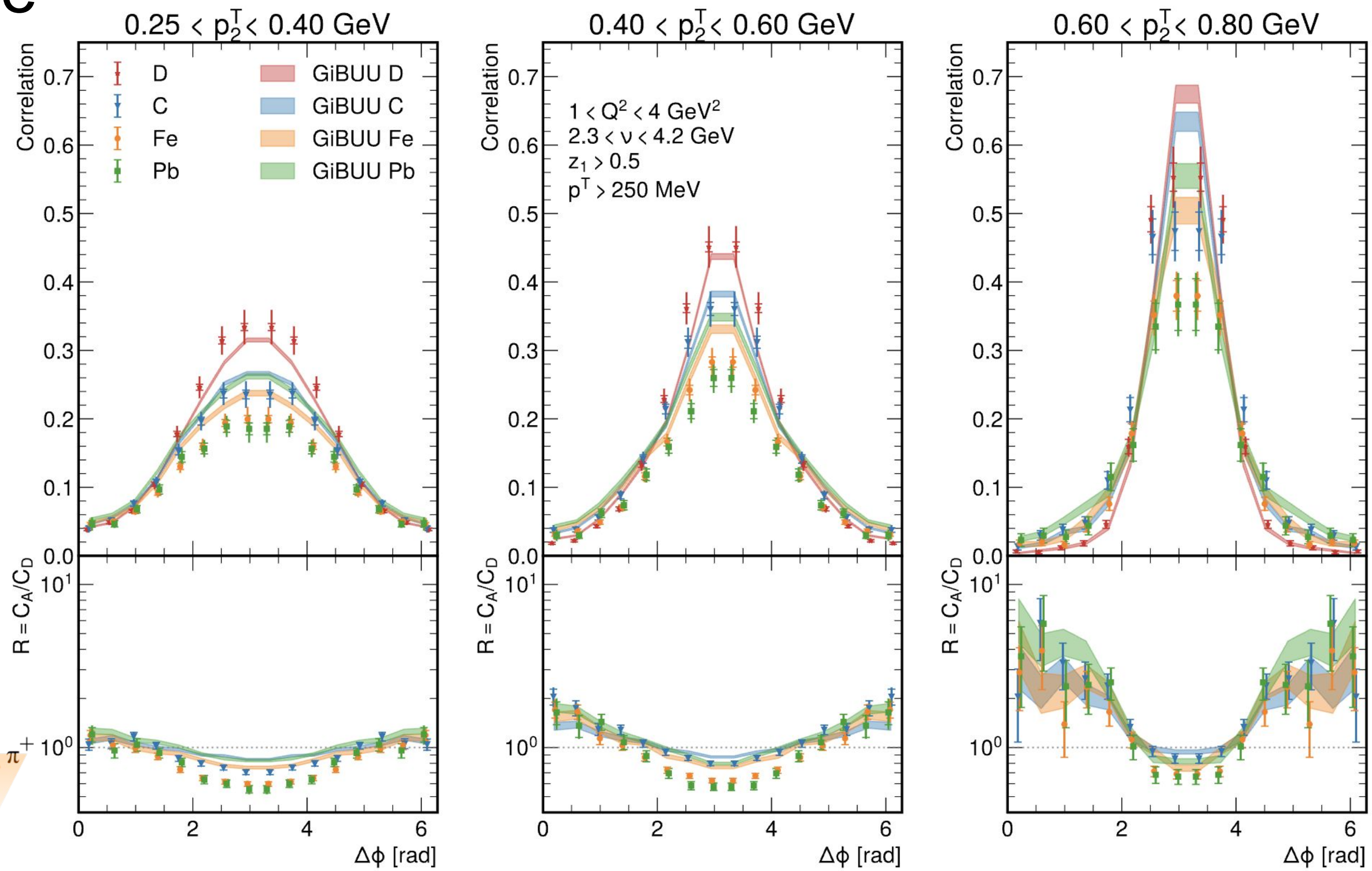


# $p_2^T$ dependence

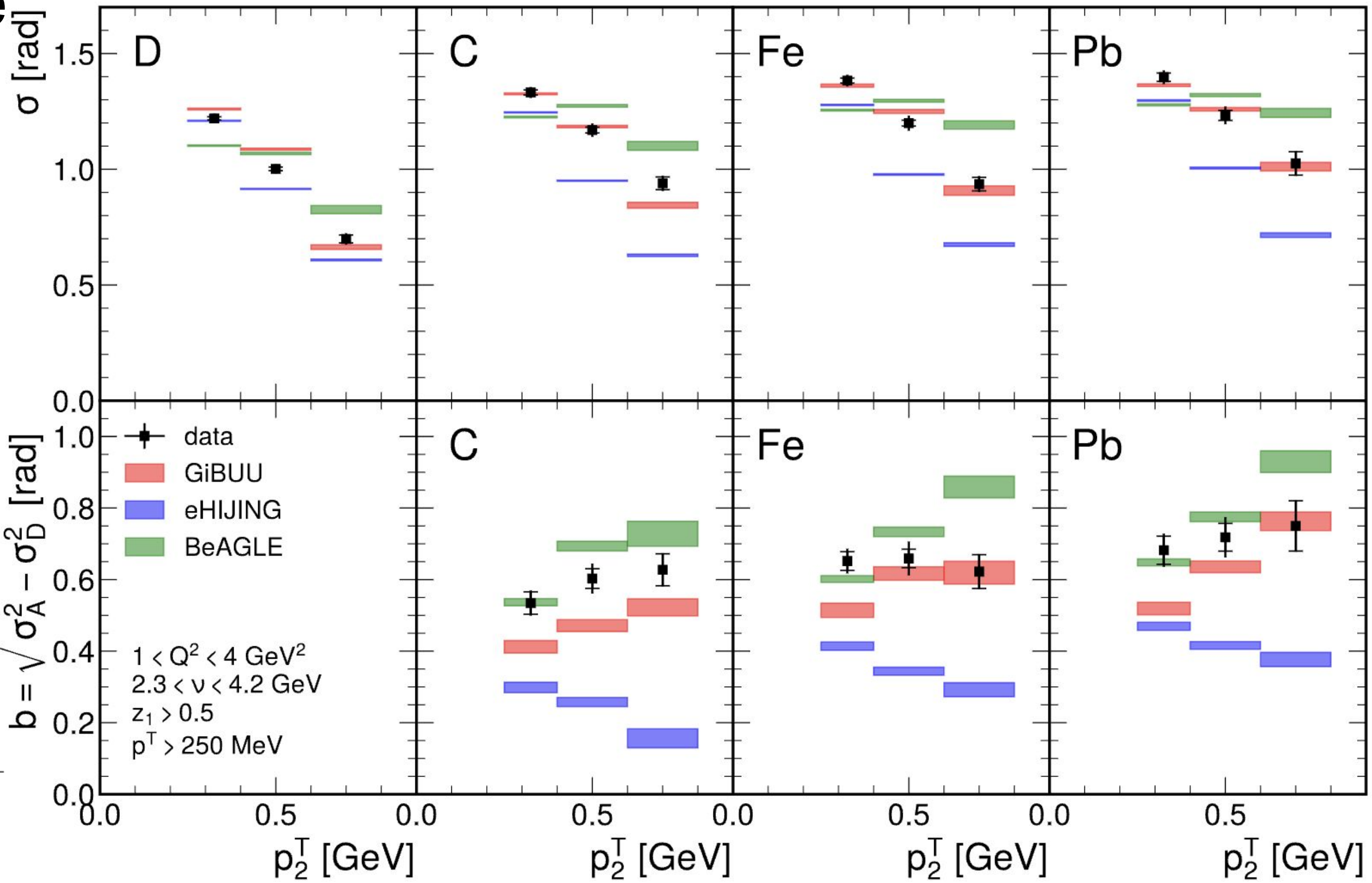
- Similar trend to the $p_1^T$ dependence

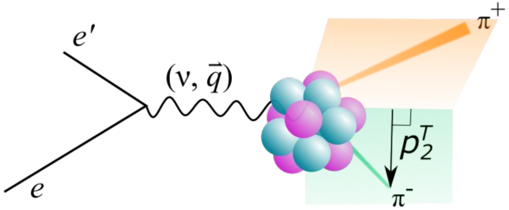


# $p_2^T$ dependence

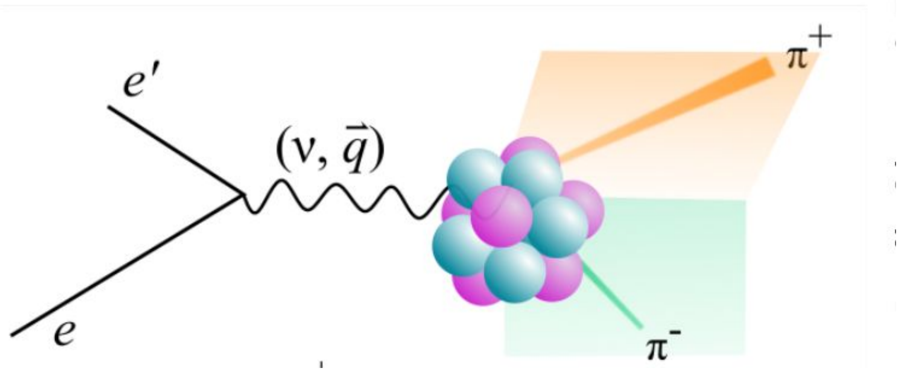
- Models predict different trends in the broadening vs $p_2^T$, which demonstrates the discriminating power of these measurements



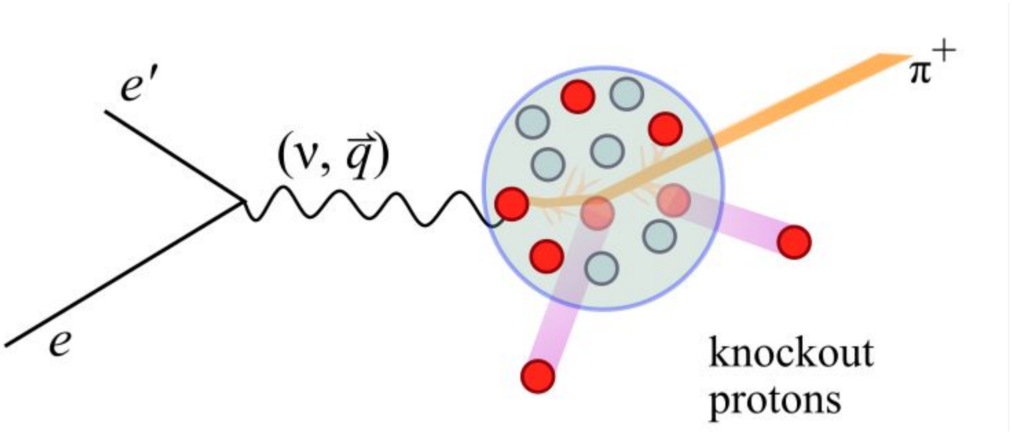
# Di-Pion Event Selection

- Electron with DIS kinematics
  - $Q^2>1$ GeV$^2$
  - W>2 GeV
  - 2.3<v<4.2 GeV
- Leading π+
  - $z=E_h/v>0.5$
  - 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<v<4.2 GeV
- Leading π+
  - $z=E_h/v>0.5$
  - 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)