Multi-dimensional analysis of correlations in di-pion electro-production off nuclei with CLAS

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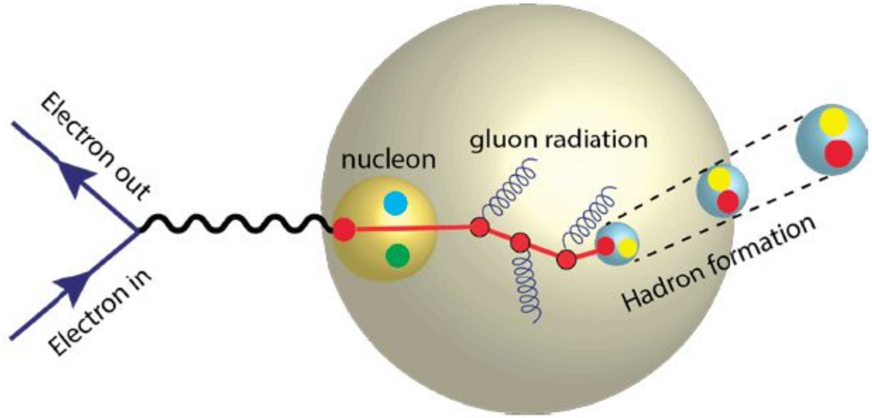
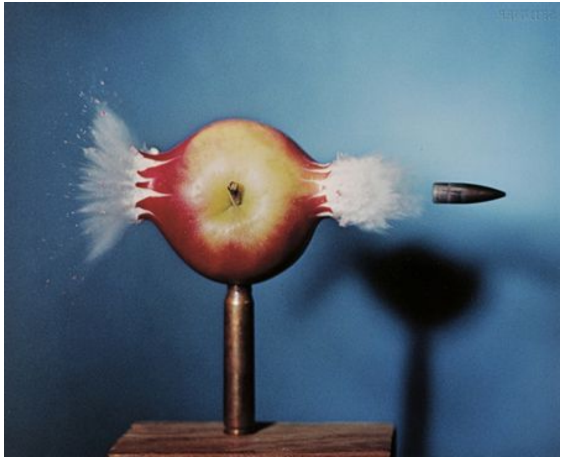
What happens when a fast quark passes through a nucleus?

- Striking a quark with an electron can dislodge it
- Measuring outgoing hadrons can reveal information about the interaction between quarks and the nucleus and also about the nuclear structure



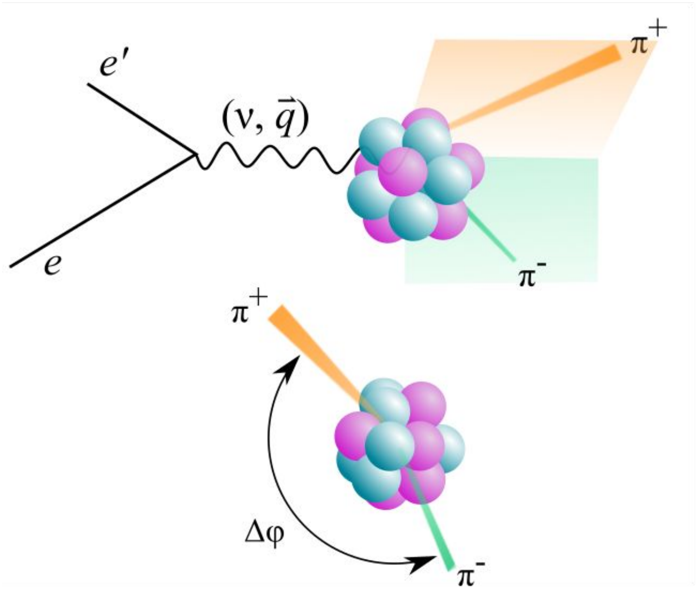


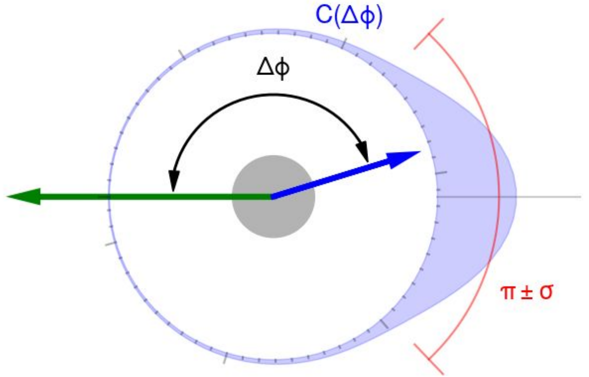
Analysis under internal review in CLAS collaboration

- Multi-dimensional measurement of the correlation function

$$C(\Delta\phi) \propto \frac{1}{N_{1h}} \frac{dN_{2h}}{d\Delta\phi}$$

  - An observable typically used in collider-type experiments; here used in a fixed-target experiment
  - Follow-up of our recent PRL paper on A/D ratios*
  - We use the convention that the integral of $C(\Delta\varphi)$ for deuterium is set to 1.





*S.J. Paul et al. (CLAS Collab.) PRL 129, 182501 (2022)

Previous results focused on A/D ratios

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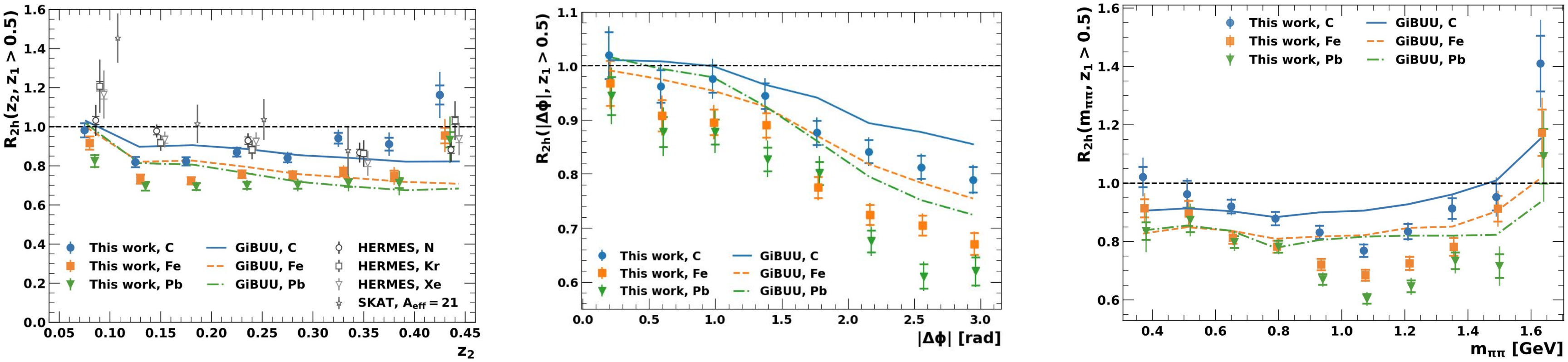
$$R_{2h} = \frac{(N_{2h}/N_h)^A}{(N_{2h}/N_h)^D} \equiv \frac{C_A}{C_D}$$

Observation of Azimuth-Dependent Suppression of Hadron Pairs in Electron Scattering off Nuclei

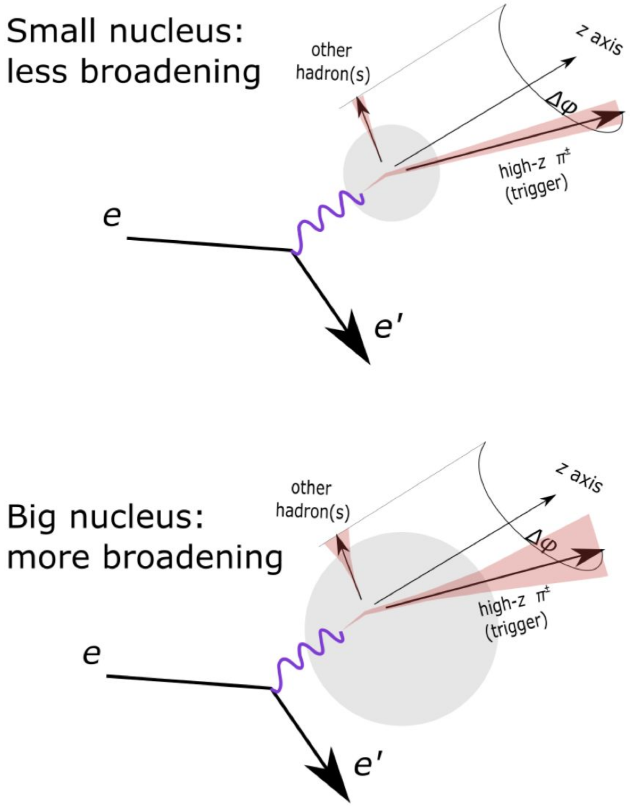
S. J. Paul *et al.* (CLAS Collaboration)

Phys. Rev. Lett. **129**, 182501 – Published 25 October 2022



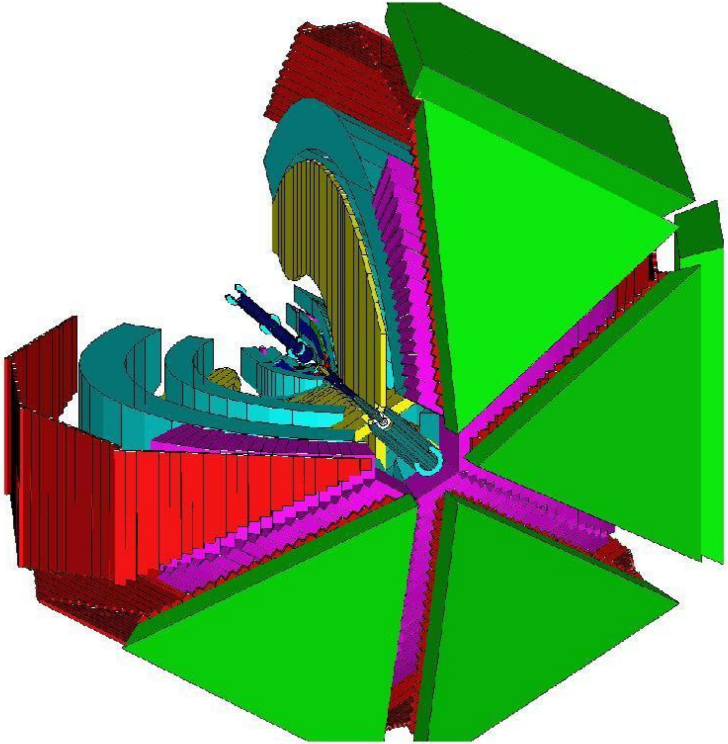
How can azimuthal correlations constrain nuclear effects?

- In bigger nuclei, the hadrons encounter more material
  - More multiple scattering
  - Angle correlations smear out more.



Dataset/Experimental Setup

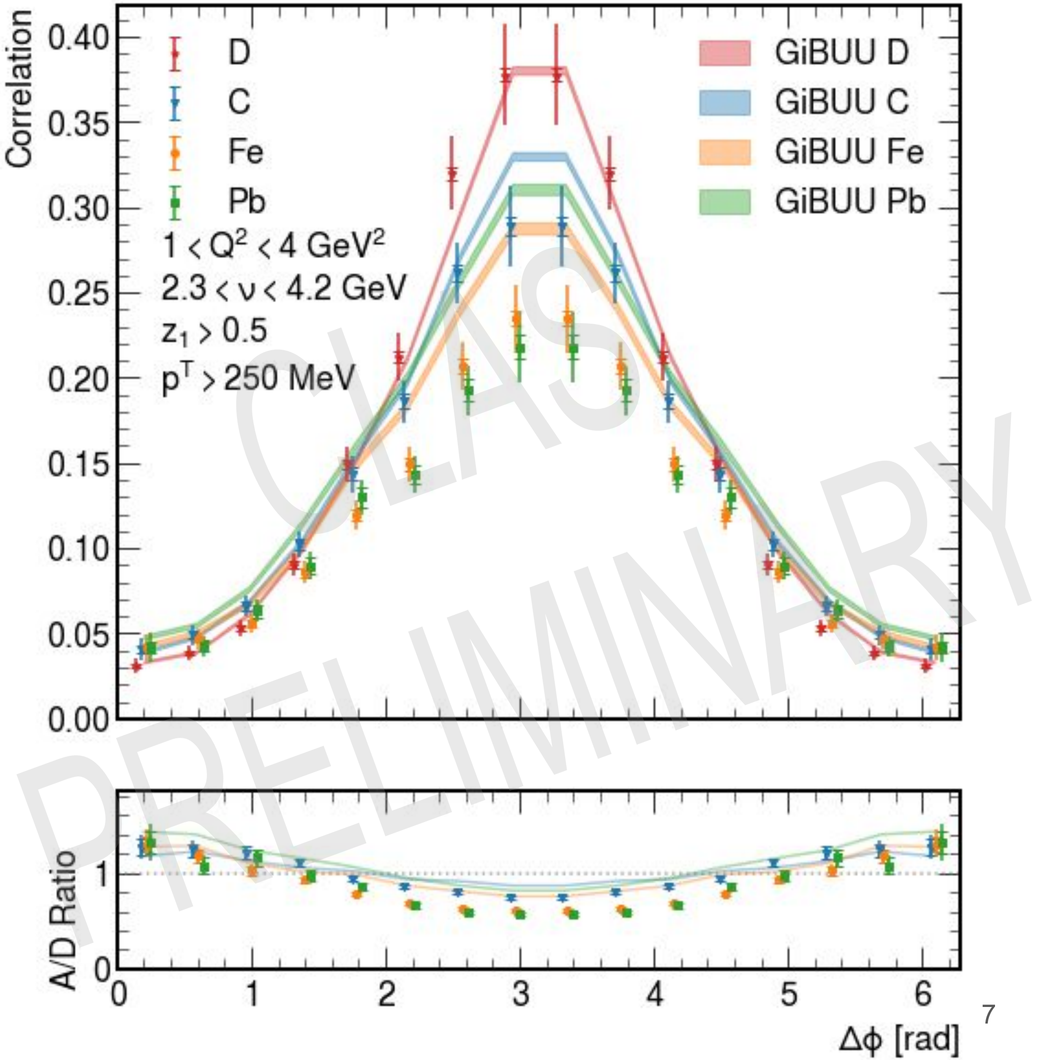
- CLAS detector at JLab
- 5 GeV e- beam
- Liquid deuterium target in tandem with nuclear targets*: C, Fe, and Pb
- Reduces systematic errors for A vs. D comparisons



*NIM A 592 (2008) 218– 223

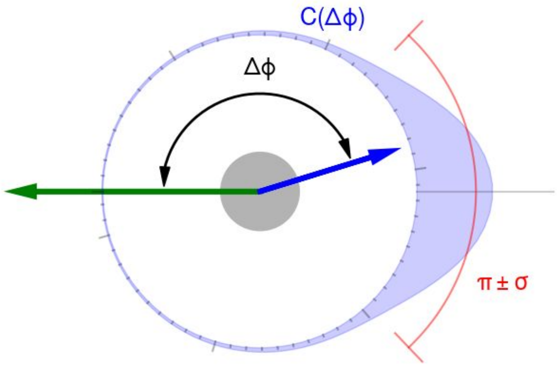
Results (integrated over kinematic variables)

- Peak at Δφ=π (azimuthally back-to-back)
- Shorter and wider peak for nuclear, with larger values in tail compared to deuterium
- Shape predicted by GiBUU for D very similar to data.
- Larger numerical discrepancies between GiBUU and data for nuclear than for D.



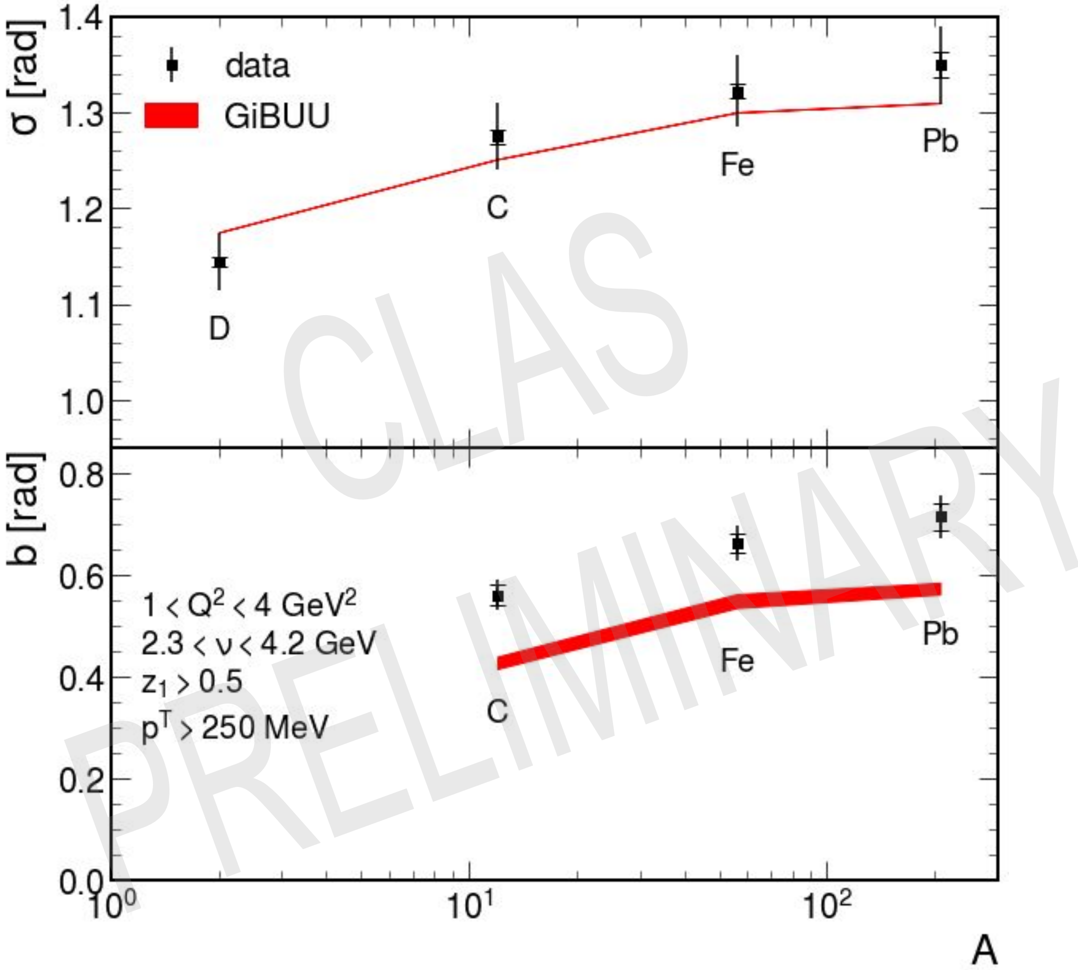
RMS widths and "broadenings"

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



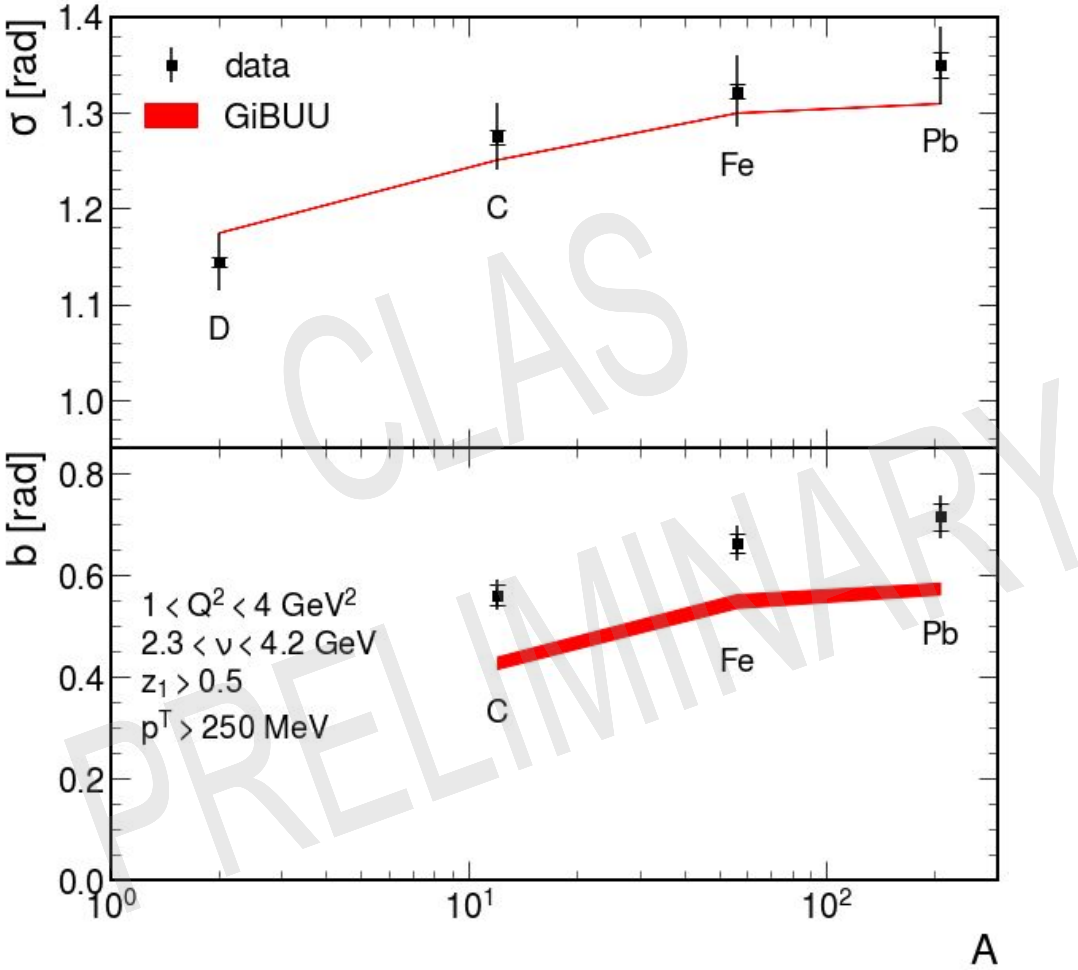
$$b = \sqrt{\sigma_A^2 - \sigma_D^2}$$

- Differences in σ between A and D can be used to probe multiple scattering inside nuclei.



RMS widths and “broadenings”

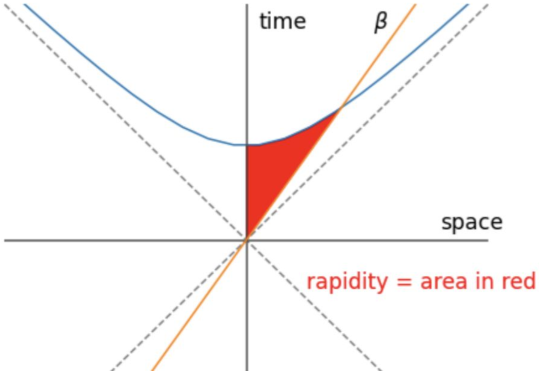
- GiBUU overpredicts width for deuterium and underpredicts for nuclear target by about 1 error bar (mostly systematic)
    - Some of these systematic uncertainties are correlated between targets
- Discrepancy between data and GiBUU becomes more clear in broadening
    - Part of the systematic uncertainty cancels out



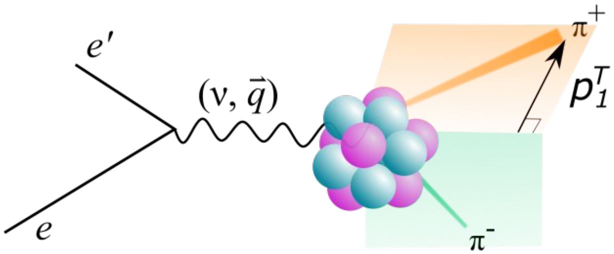
Multidimensional binning of the correlation function

Rapidity difference, ΔY

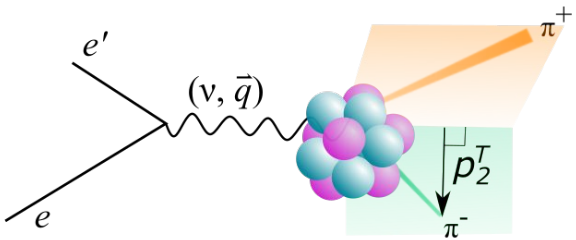
$$Y = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$



Transverse momentum of leading pion



Transverse momentum of sub-leading pion

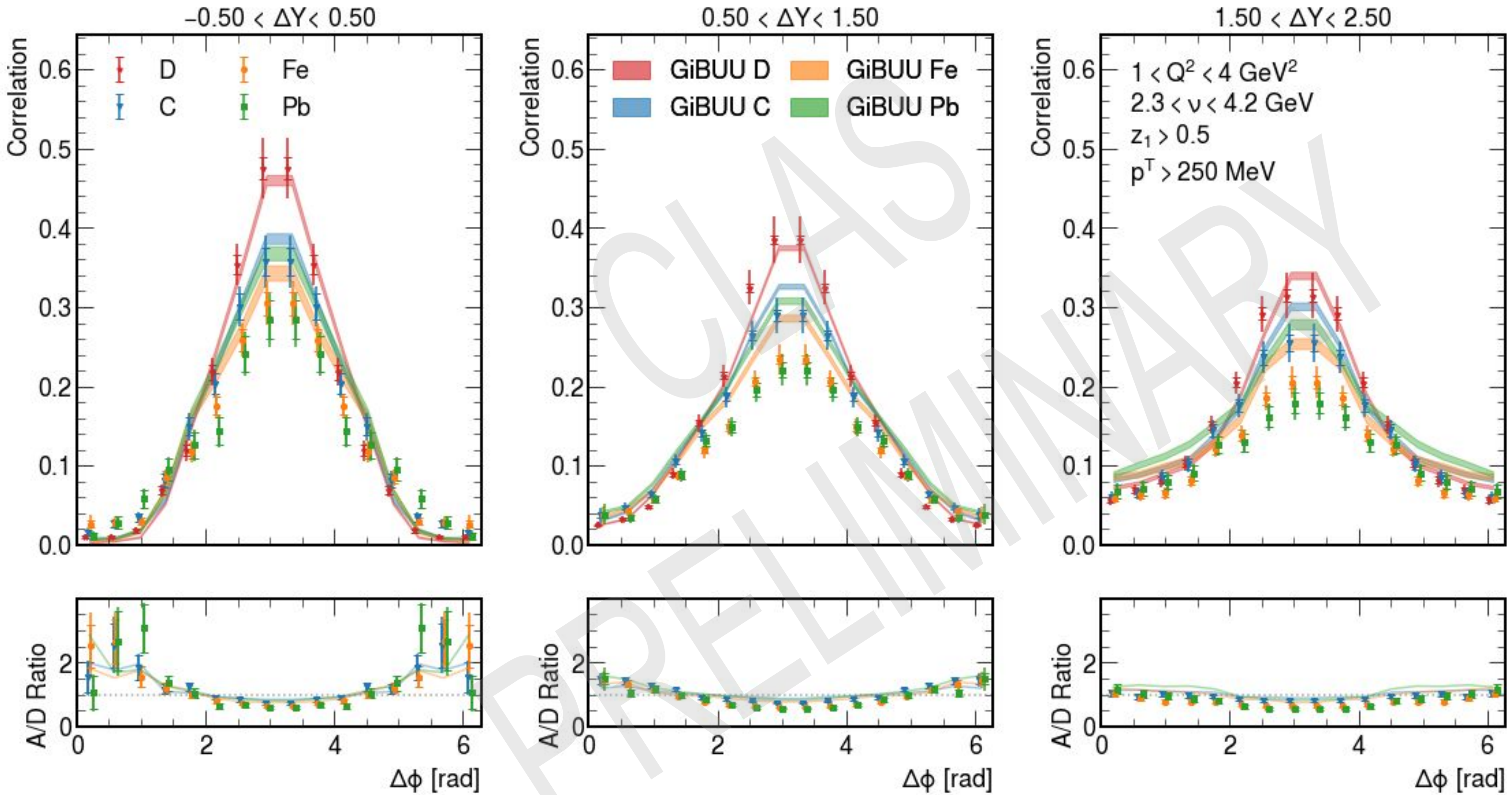


Rapidity dependence of C(ΔΦ)

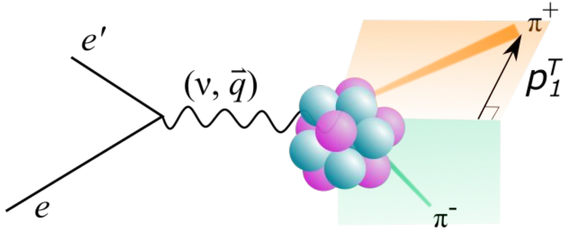
$\Delta Y = Y_1 - Y_2$

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

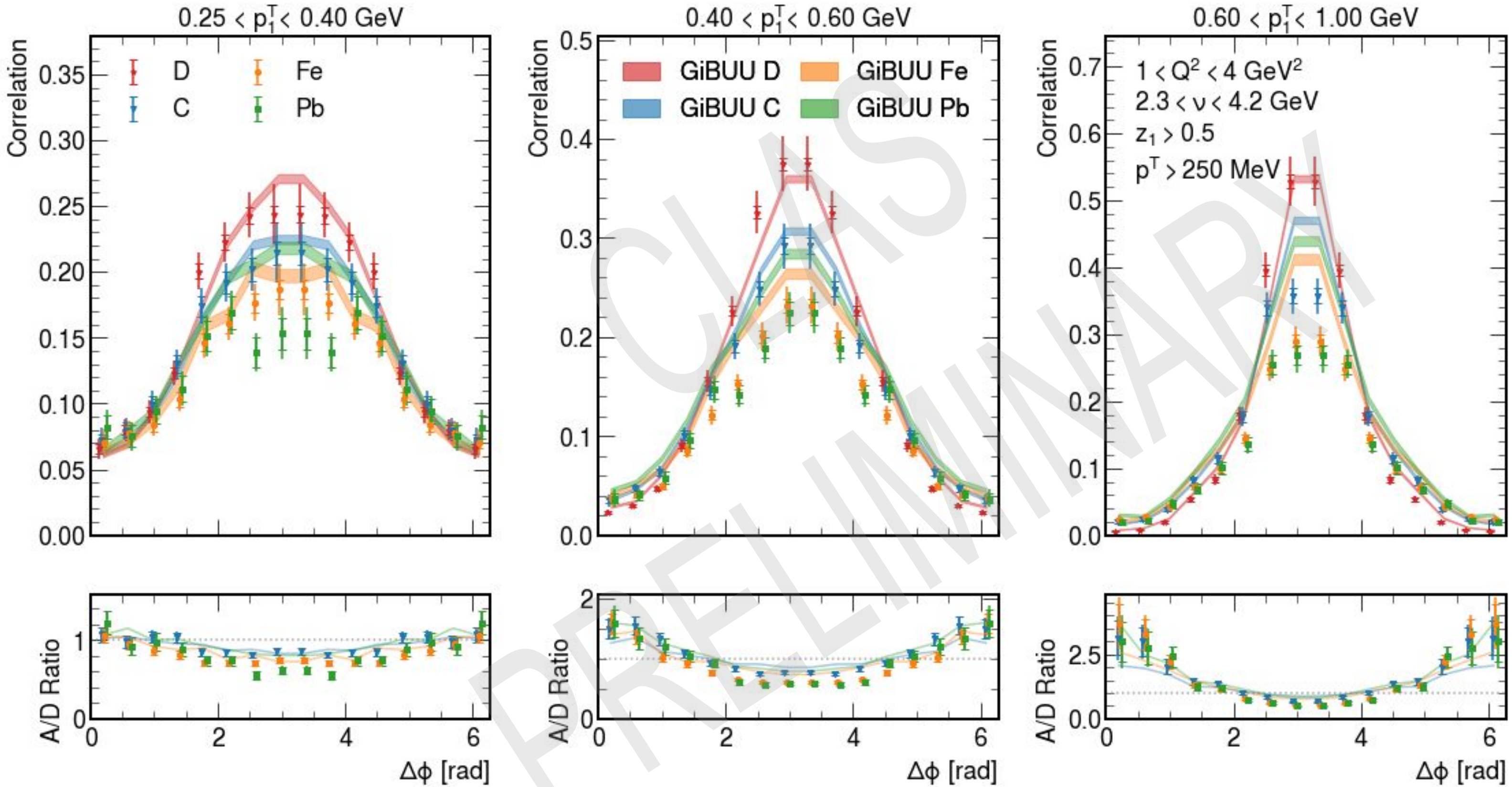
- Large discrepancy between data and model at ΔY, Δφ near 0



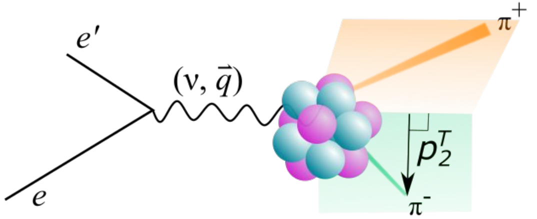
Transverse momentum of leading pion



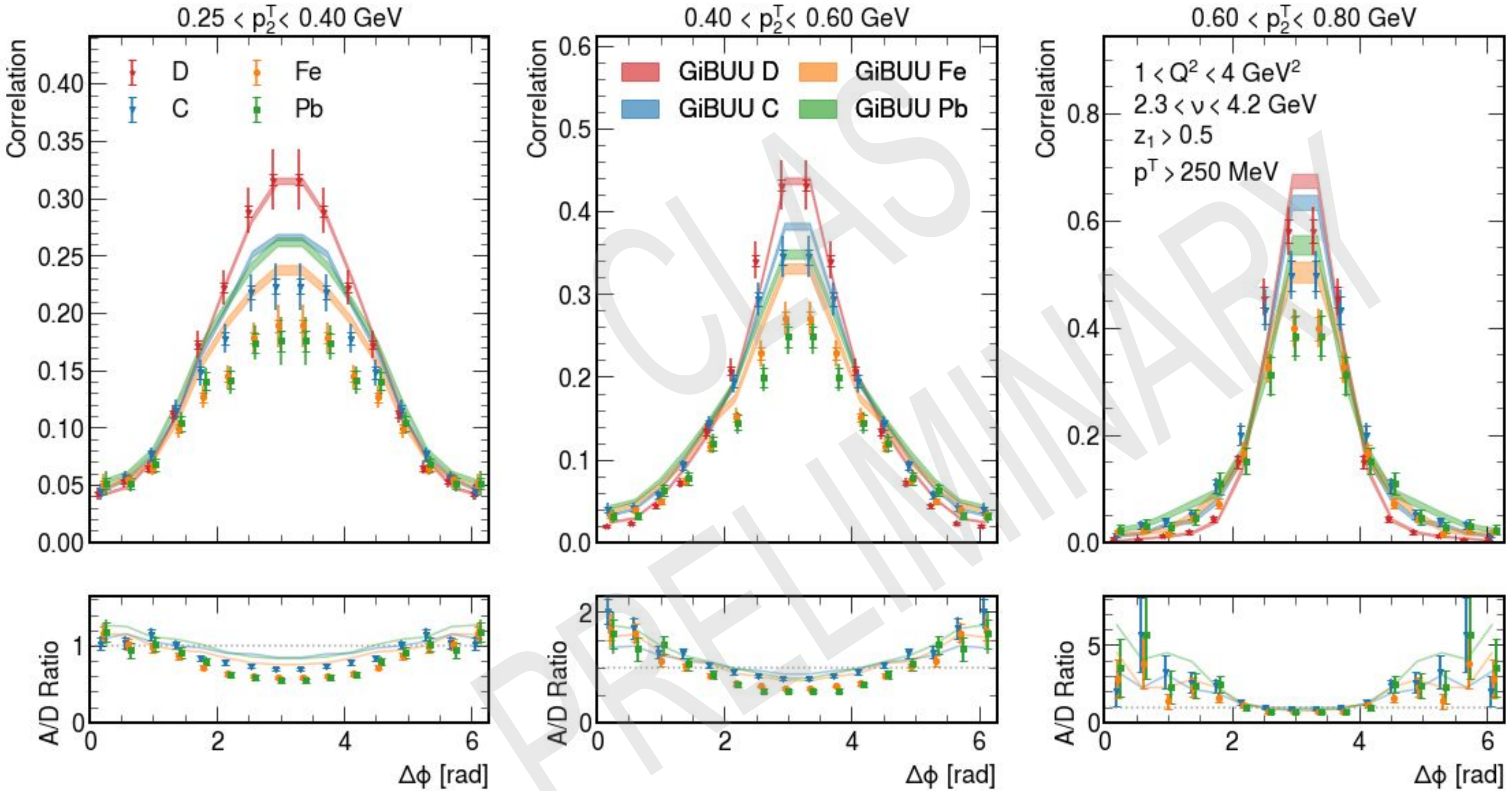
- Narrower correlations with larger p_1^T



Transverse momentum of sub-leading pion

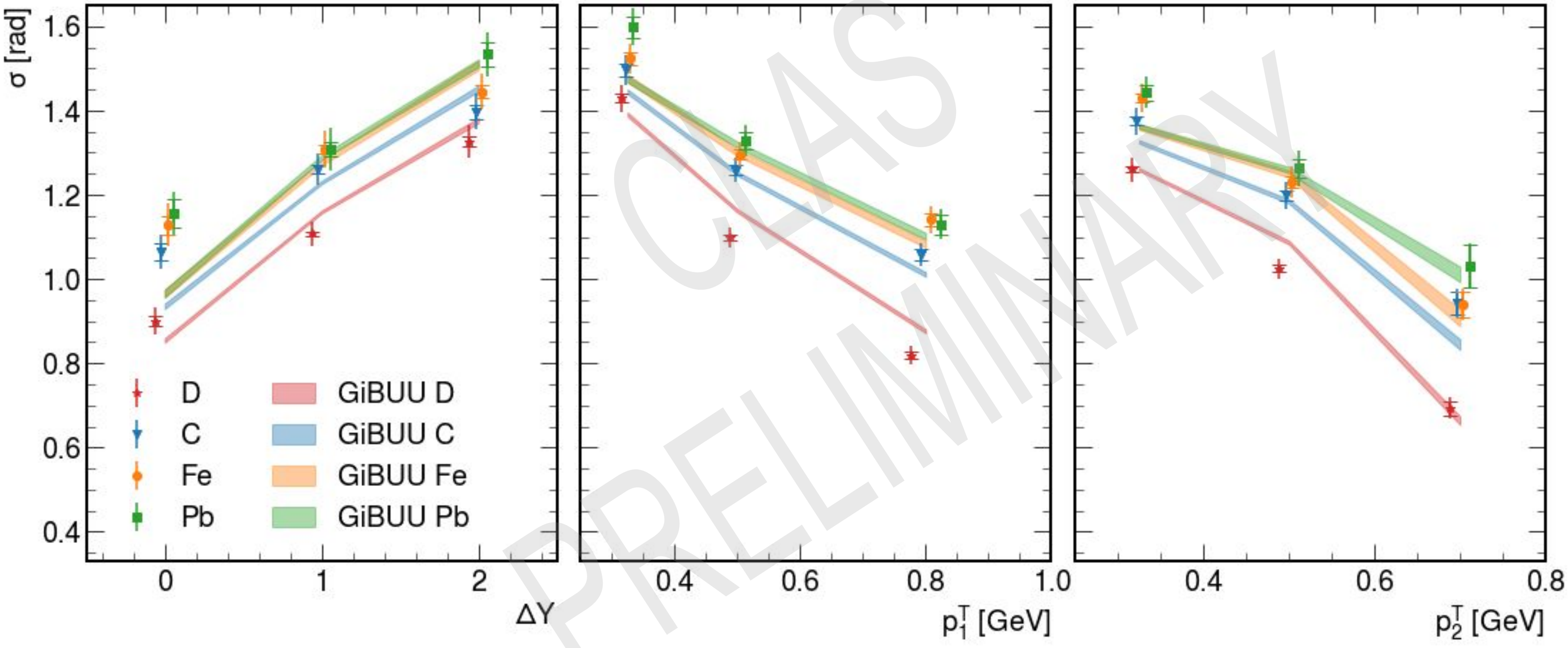


- Narrower correlations with larger p_2^T as well.



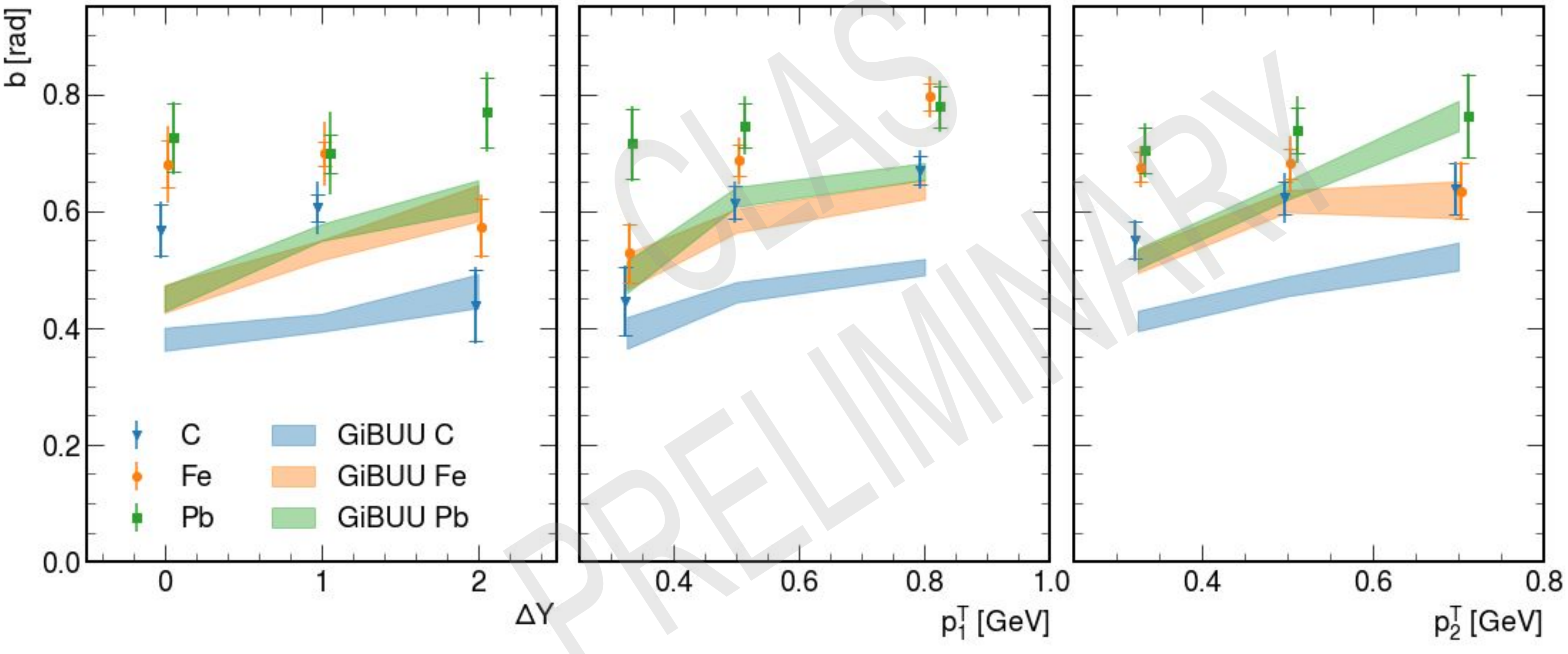
Widths of correlation functions (RMS)

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



Broadening of correlation functions

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



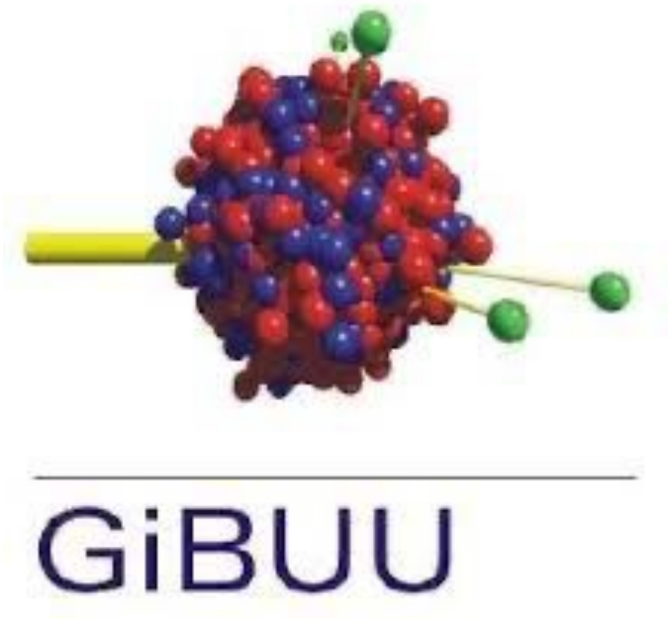
Summary

- Measuring the di-hadron azimuthal correlation functions for D and nuclear targets is a useful tool for probing hadron-nucleus interactions
- $C(\Delta\varphi)$ has a peak at $\Delta\varphi=\pi$, tails at 0 (2π)
- Larger nuclei have wider and shorter peaks, with larger values in the tails, compared to deuterium
- Introduced summary observables:
  - RMS widths can quantify the change of shape of the correlation functions.
    - Decreases with transverse momentum of either hadron. Increases with increasing rapidity difference
  - "Broadenings" can be used to isolate and quantify nuclear effects such as multiple scattering.
- Analysis is under internal review with the CLAS collaboration.

Backup slides

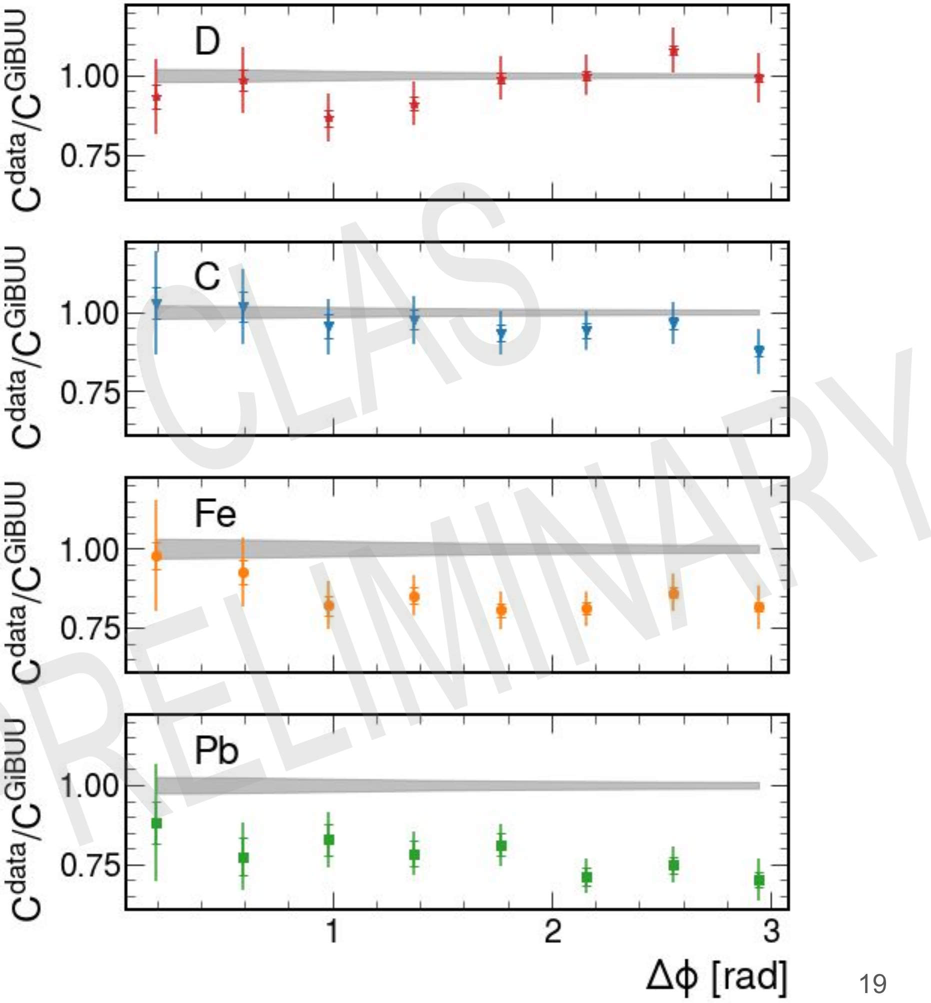
GiBUU model

- 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



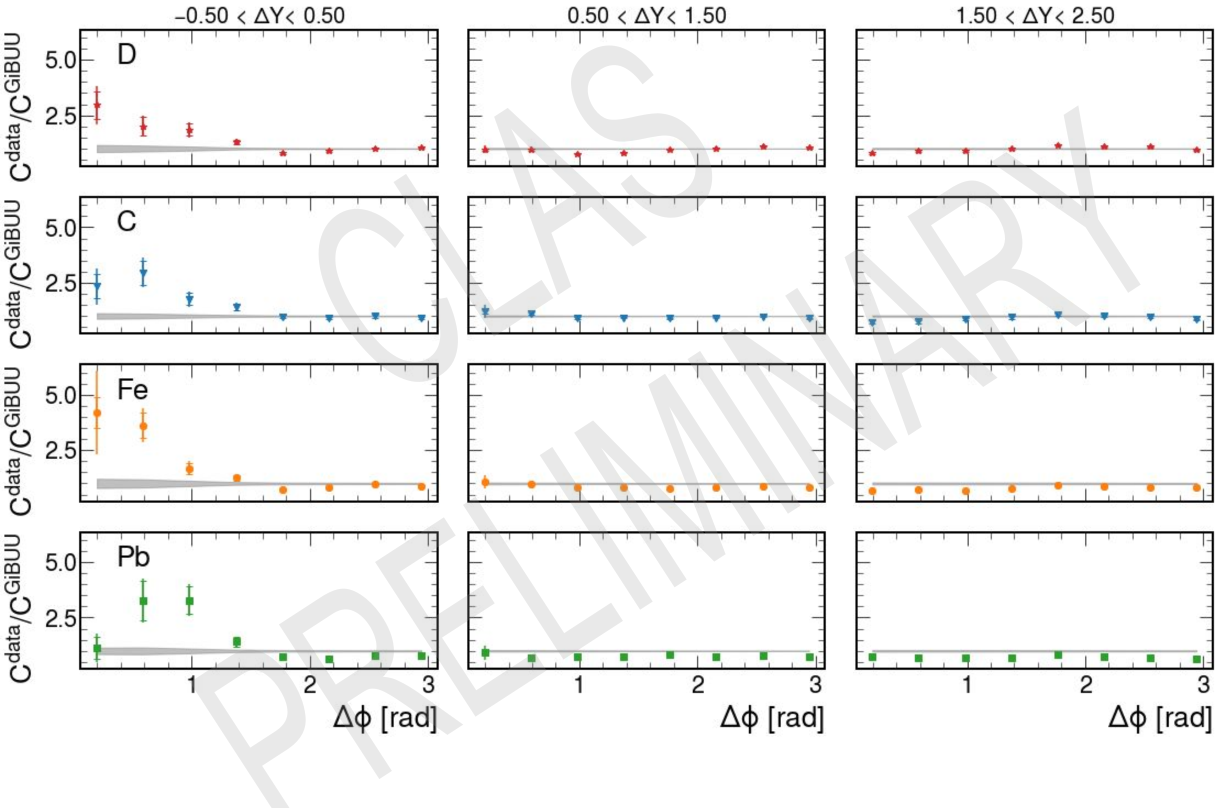
Data/GiBUU ratios

- Reasonable agreement for D and C
- Fe and Pb: Deviation of about -20% to -25%; no trend in Δφ
    - Largely a difference in normalization



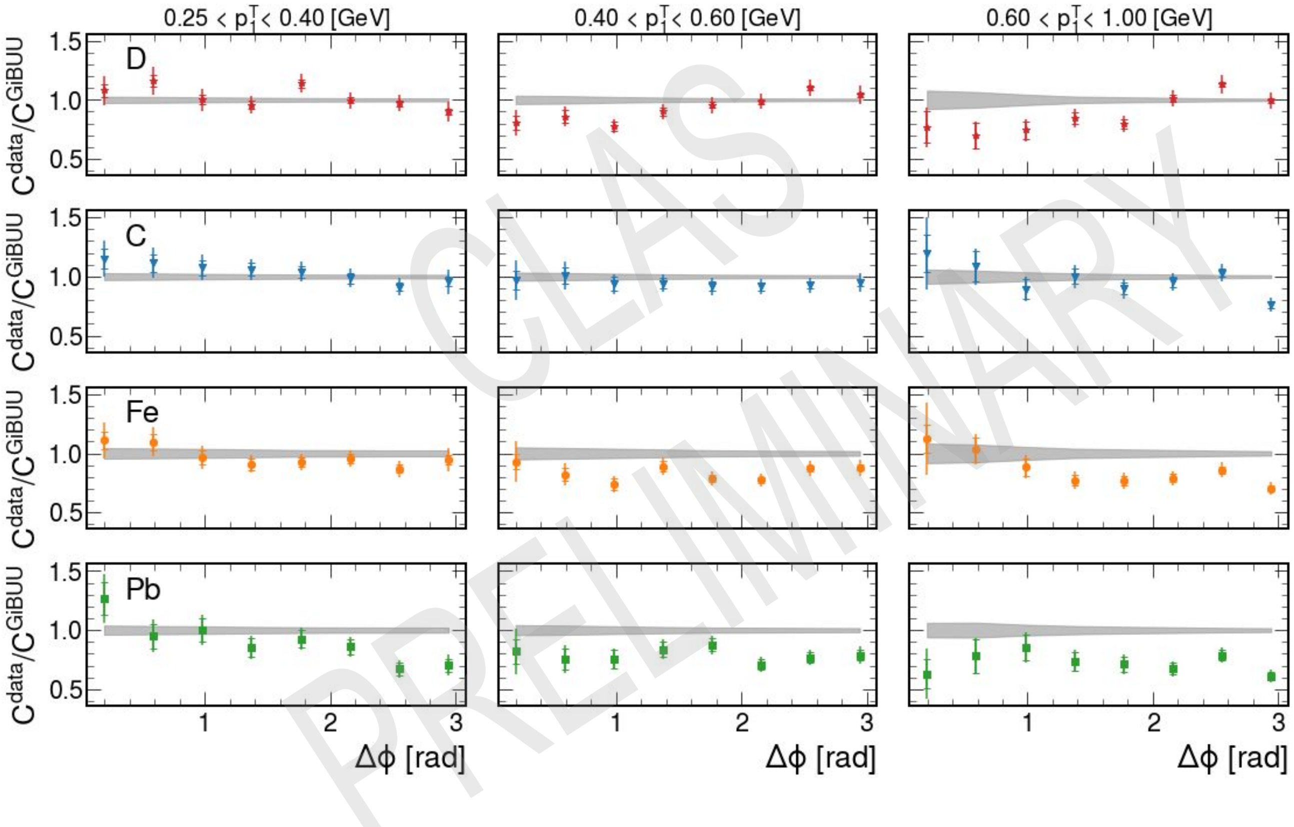
Data/GiBUU ratios: ΔY slices

- Large excess in data at low ΔY and Δφ
- Some ingredient may be missing in GiBUU model



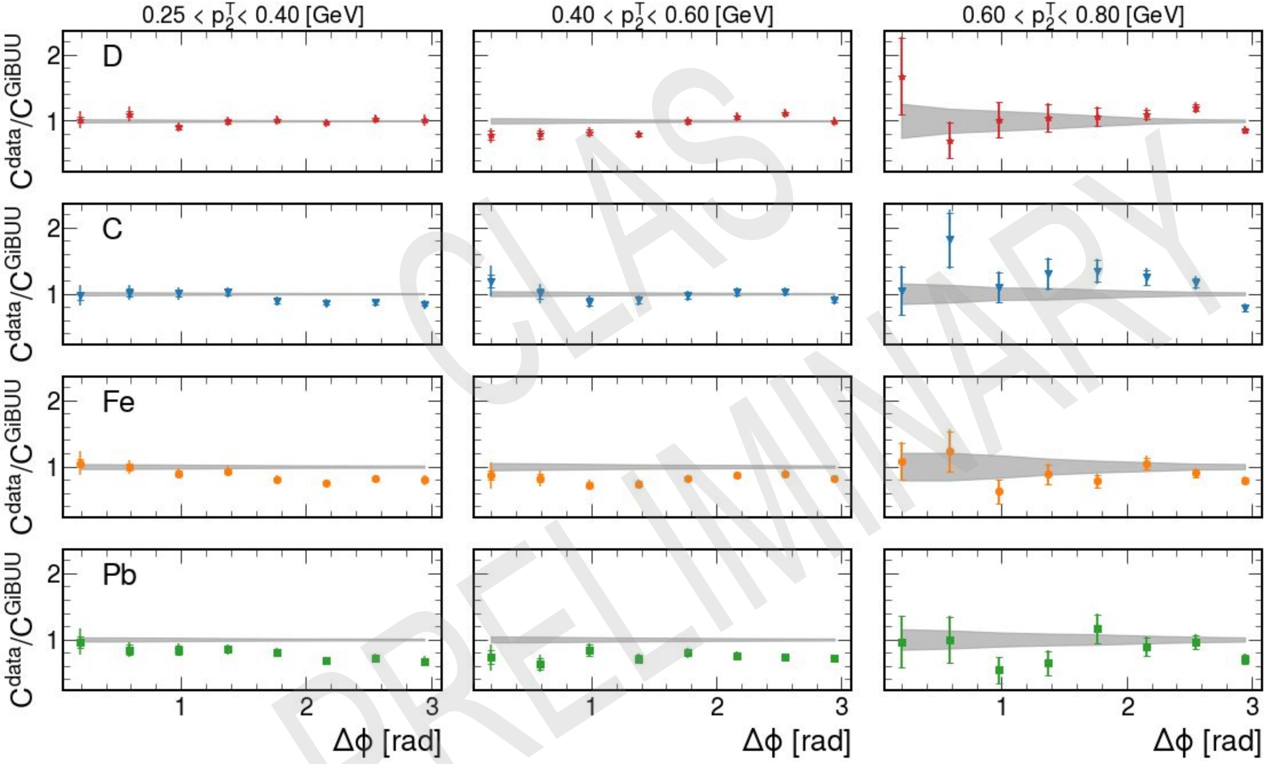
Data/GiBUU ratios: p^T_1 slices

Not as dramatic trends in deviations as observed in ΔY slices.



Data/GiBUU ratios: p^T_2 slices

Again, not as dramatic trends in deviations as observed in ΔY slices



Systematic uncertainties summary (C and R2h)

- Some systematic uncertainties are large for specific multidimensional bins

Source	$\Delta C/C$ (D)	$\Delta C/C$ (A)	corr. A vs D?	type	$\Delta R_{2h}/R_{2h}$
Statistics	1.1–38.8%	1.8–43.8%	N	p2p	2.2–52.7%
Particle misid.	0.0–16.7%	0.0–39.5%	Y	p2p	0.0–27.4%
Event selection	0.2–11.4%	0.2–11.4%	Y	p2p	0.1–21.5%
Pair acceptance	6.2%	6.2%	Y	p2p	2.0%
Endcaps	0.1–2.6%	–	N	p2p	0.1–2.6%
Luminosity	negligible	negligible	–	–	negligible
Trigger efficiency	negligible	negligible	–	–	negligible
Time dependent effects	negligible	negligible	–	–	negligible
Coulomb effects	negligible	negligible	–	–	negligible
Bin migration	negligible	negligible	–	–	negligible
Syst. subtotal	6.2–21.2%	6.2–41.6%	–	–	2.0–31.2%
Total	6.4–40.1%	6.7–57.0%	–	–	3.1–55.3%

Table 7.2: Summary of statistical and systematic uncertainties on the correlation functions from various sources, listed separately for deuterium (D) and for the nuclear targets (A). We also list the uncertainties for the ratio $R = C_A/C_D$, and note whether the systematic errors for the correlation functions are correlated between the nuclear and deuterium targets. A "p2p" (point-to-point) type of uncertainty affects each bin by a different amount (though there may be some correlation between the bins), whereas a "norm" (normalization) type uncertainty affects every bin proportionally by the same amount.

Systematic uncertainties summary (σ and b)

- Relative systematic uncertainties for σ and b are considerably smaller

Source	$\Delta\sigma/\sigma$ (D)	$\Delta\sigma/\sigma$ (A)	corr. D vs A?	$\Delta b/b$
Statistics	0.4–2.5%	0.6–4.9%	N	2.7–14.1%
Particle misid.	0.1–0.8%	0.2–2.9%	Y	0.3–8.7%
Event selection	0.9–2.5%	0.9–2.5%	Y	0.3–3.8%
Pair acceptance	1.0–1.4%	0.9–1.2%	Y	1.4–1.4%
Endcaps	0.0–0.1%	–	N	0.0–0.2%
Finite bin width	0.1–1.4%	0.0–0.7%	Y	0.4–0.7%
Luminosity	negligible	negligible	–	negligible
Trigger efficiency	negligible	negligible	–	negligible
Time dependent effects	negligible	negligible	–	negligible
Coulomb effects	negligible	negligible	–	negligible
Bin migration	negligible	negligible	–	negligible
Syst. subtotal	1.9–3.2%	2.0–4.1%	Y	2.4–9.0%
Total	2.0–3.8%	2.2–5.4%	Y	4.5–14.8%

Table 7.3: Summary of statistical systematic uncertainties on the widths and broadenings from various sources, listed separately for deuterium (D) and for the nuclear targets (A). The third column represents whether or not there is some correlation between the uncertainties on the widths for the nuclear and deuterium targets.