Multi-dimensional analysis of correlations in di-pion electro-production off nuclei with EG2 data

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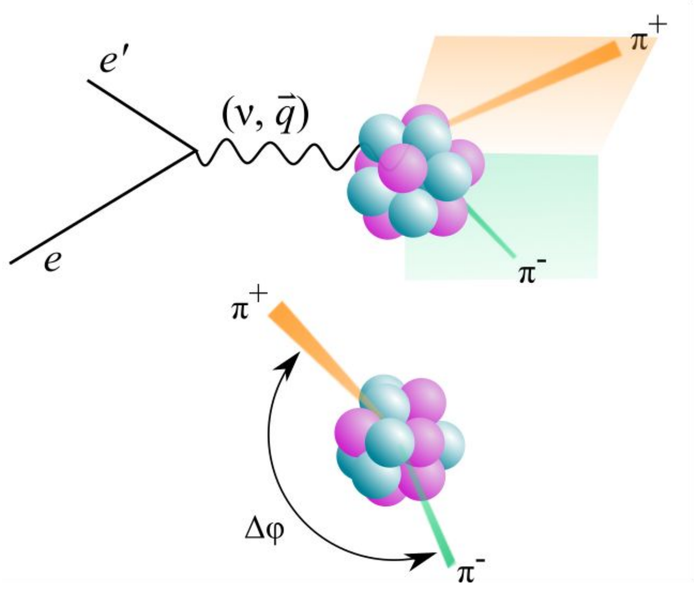
CLAS Collaboration Meeting 3/23/2023

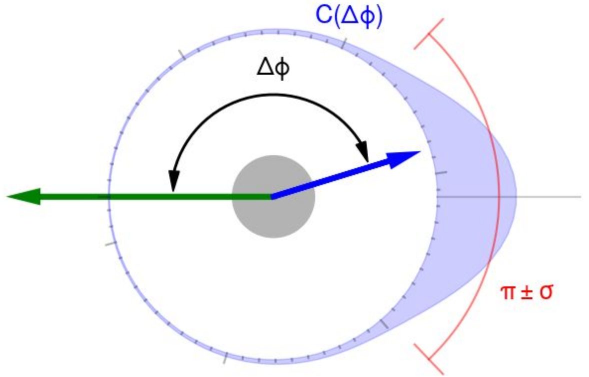
Analysis note draft under review

- Follow-up to the previous di-pion in nuclear DIS paper
- Multiple dimensional study
- Focuses on a new observable

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

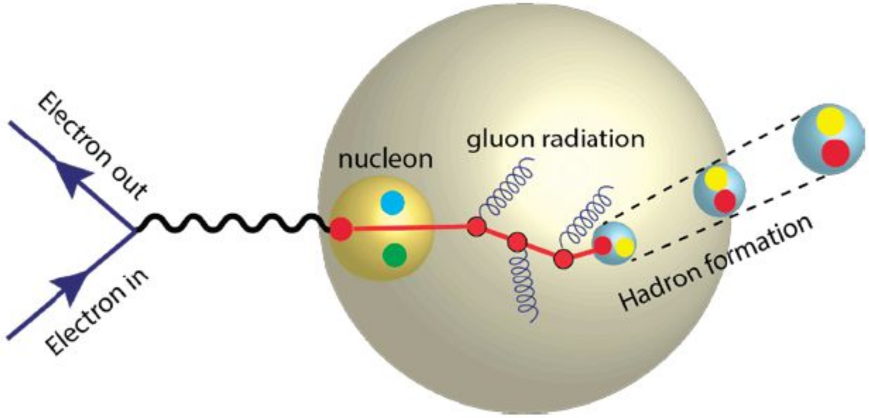
  - “correlation function”, often used in collider-based experiments
  - We use the convention a convention that the integral of $C(\Delta\varphi)$ for deuterium is set to 1.





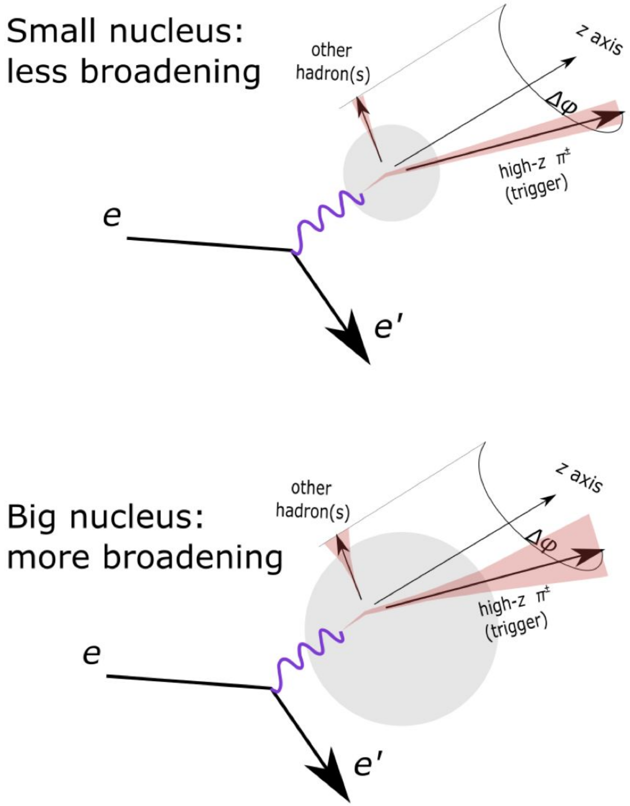
What happens when a fast quark passes through a nucleus?

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



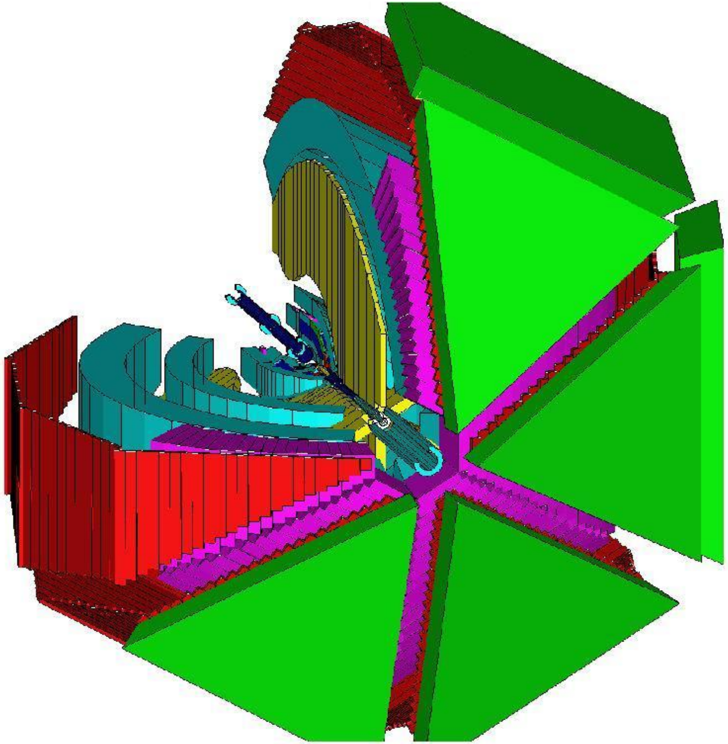
How can nuclear effects be constrained by azimuthal correlations?

- In bigger nuclei, the hadrons encounter more material → angle correlations smear out more.
- Sensitive to correlation effects induced by nuclear interactions.



Dataset/Experimental Setup

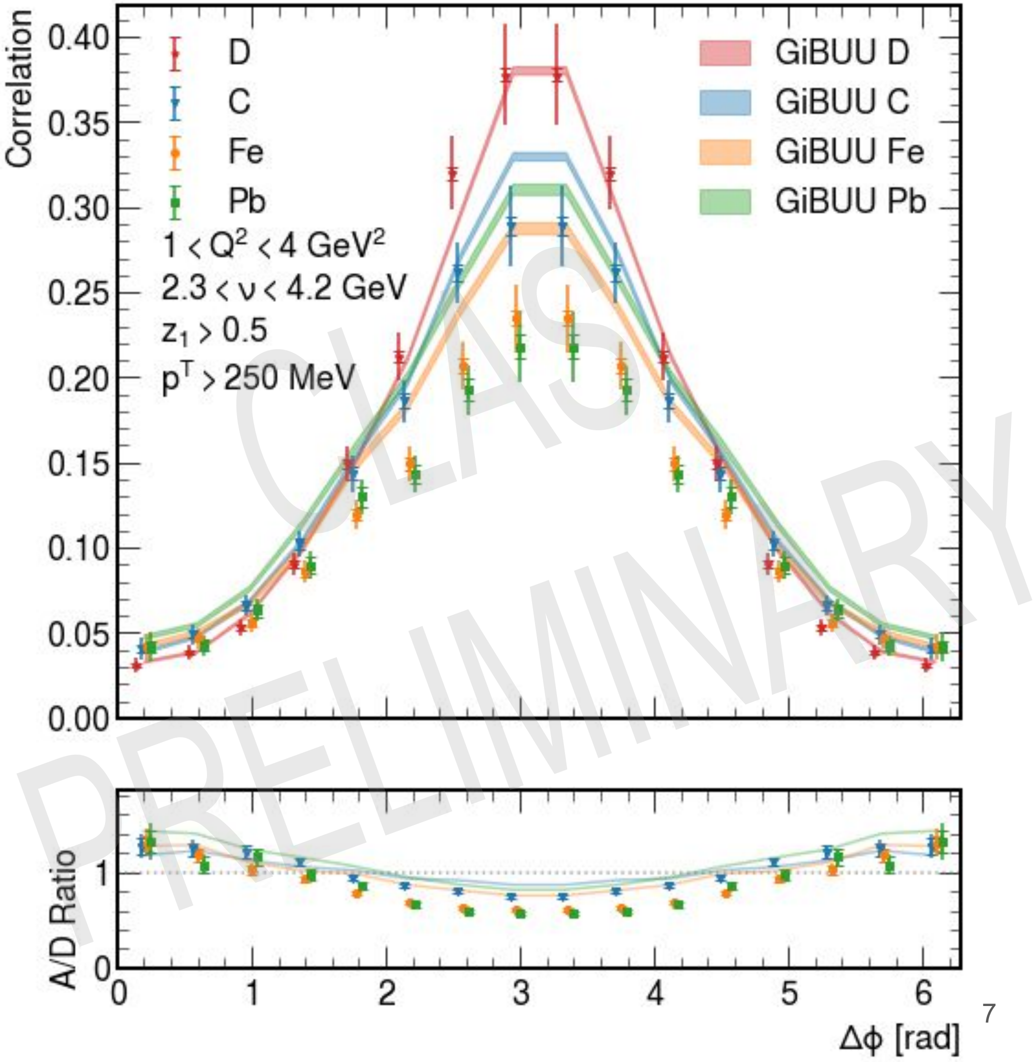
- EG2 dataset with CLAS detector
- 5 GeV e- beam
- Liquid deuterium in tandem with nuclear targets*: C, Fe, and Pb
- Reduces systematic errors for A vs. D comparisons



*NIM A 592 (2008) 218– 223

Results (integrated over kinematic variables)

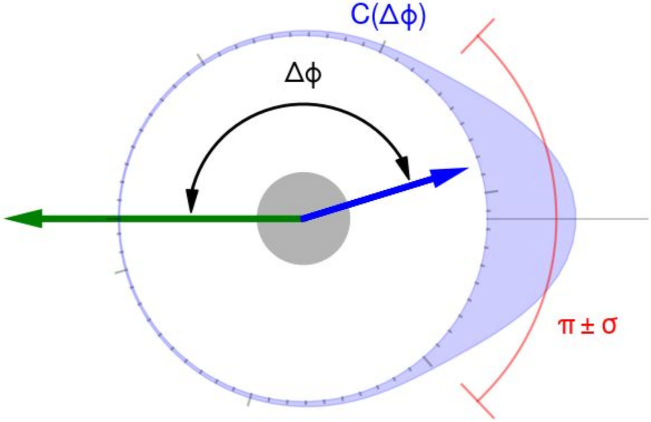
- Peak at Δφ=π (azimuthally back-to-back)
- Shorter and wider peak for nuclear, with larger values in tail compared to deuterium
- Shape predicted by GiBUU for D very similar to data.
- Larger numerical discrepancies between GiBUU and data for nuclear than for D.

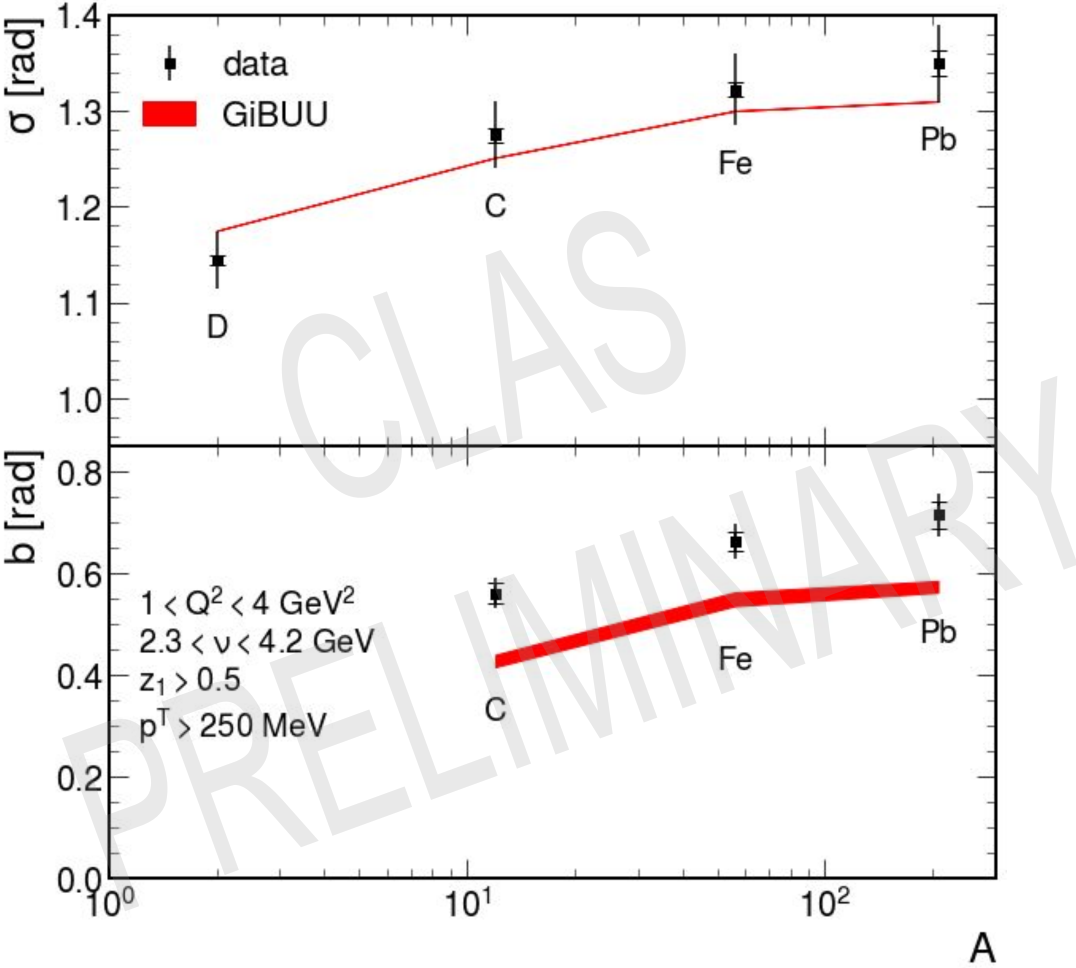


RMS widths and “broadenings”

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

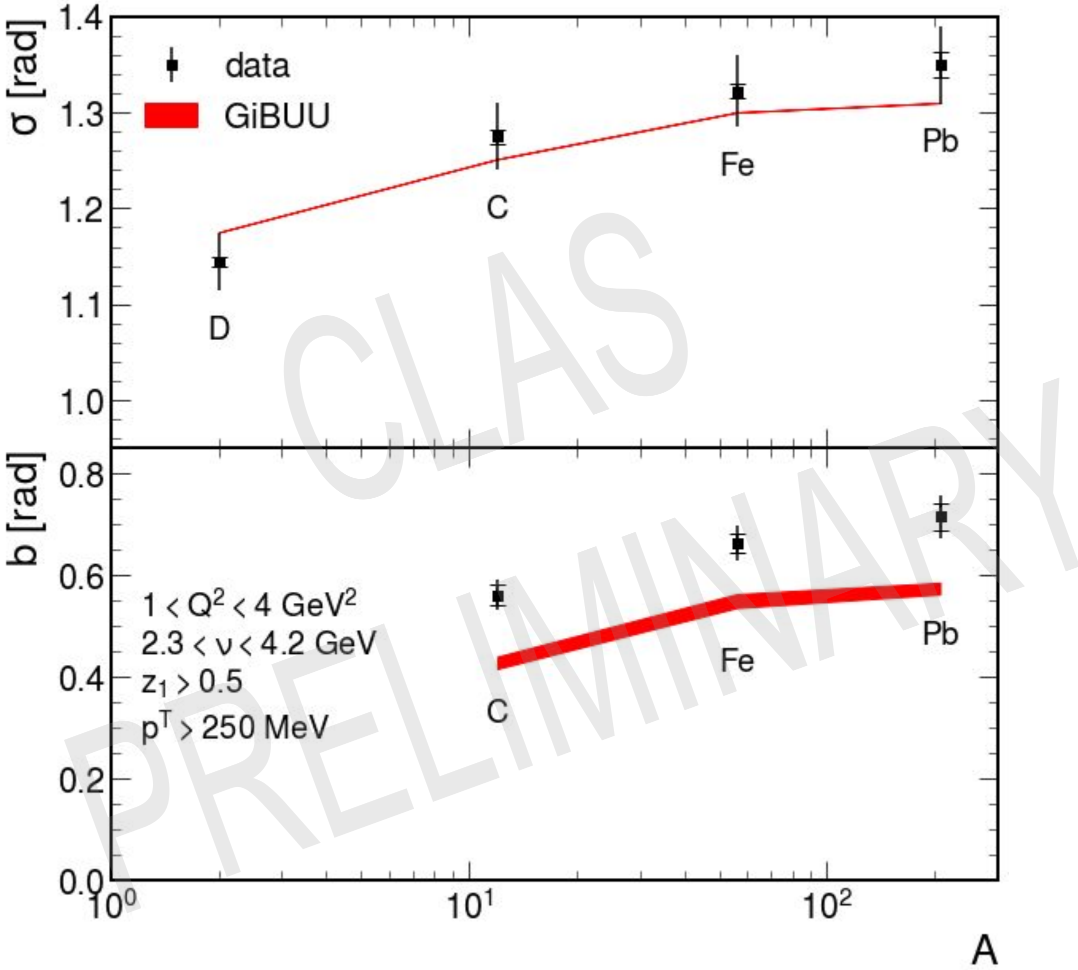
$$b = \sqrt{\sigma_A^2 - \sigma_D^2}$$





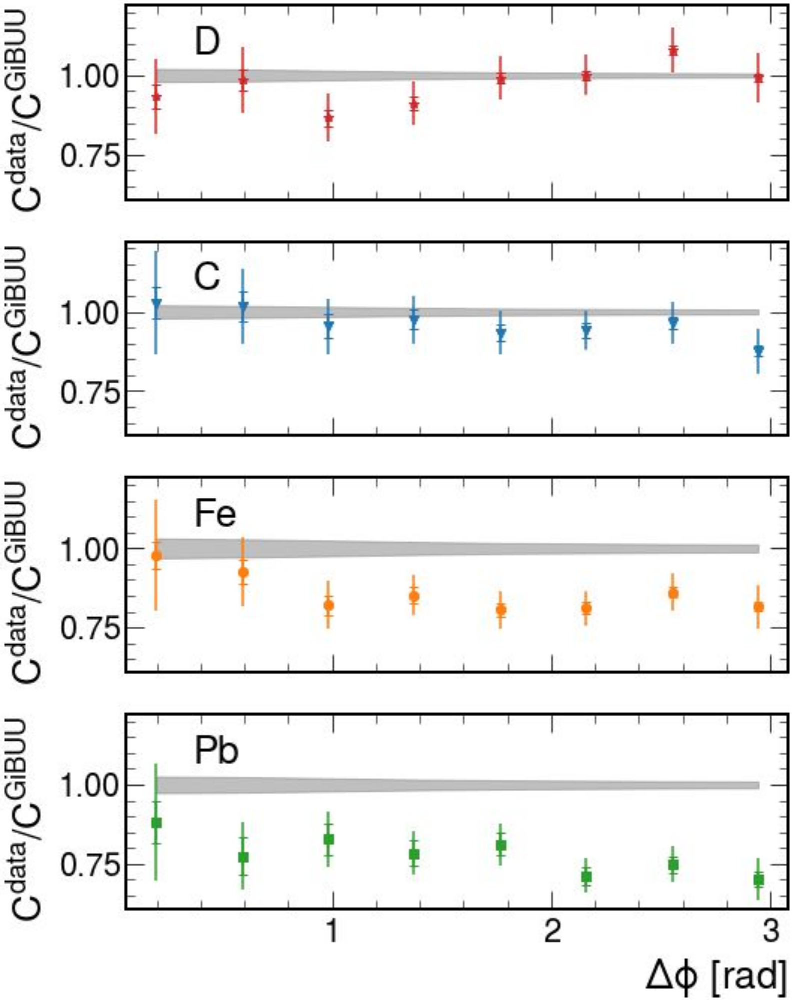
RMS widths and “broadenings”

- GiBUU overpredicts width for deuterium and underpredicts for nuclear target by about 1 sigma (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



Data/GiBUU ratios

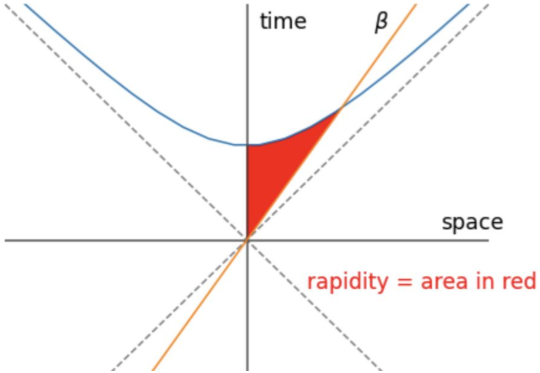
- Reasonable agreement for D and C
- Fe and Pb: Deviation of about -20% to -25%; no trend in Δφ
    - Seems to be a difference in normalization



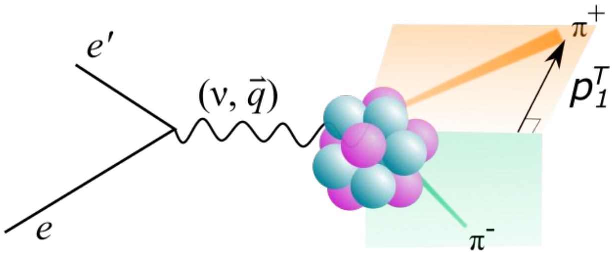
Multidimensional binning of the correlation function

Rapidity difference, ΔY

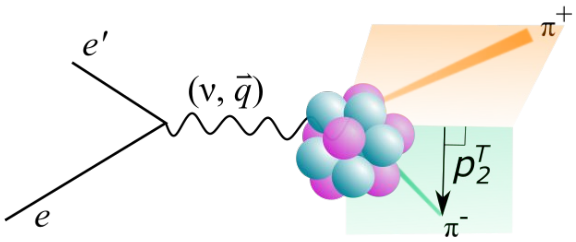
$$Y = \frac{1}{2} \ln \frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$



Transverse momentum of leading pion



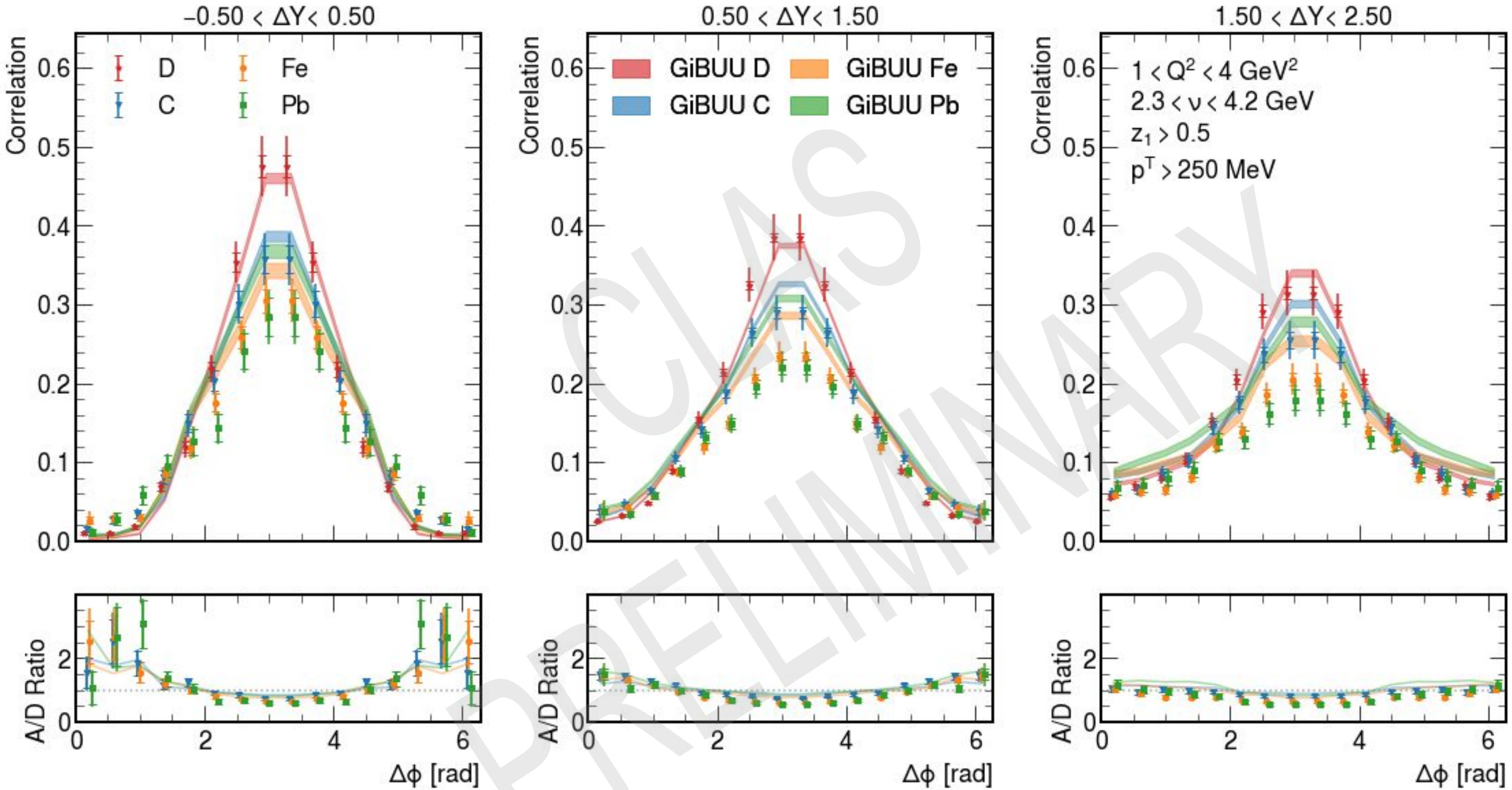
Transverse momentum of sub-leading pion



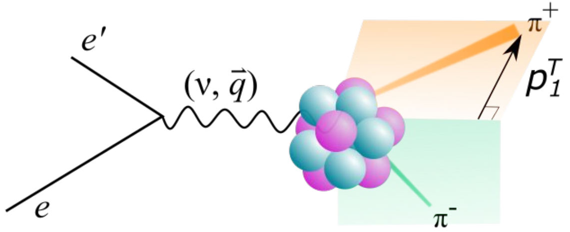
Rapidity dependence of C(ΔΦ)

$\Delta Y = Y_1 - Y_2$

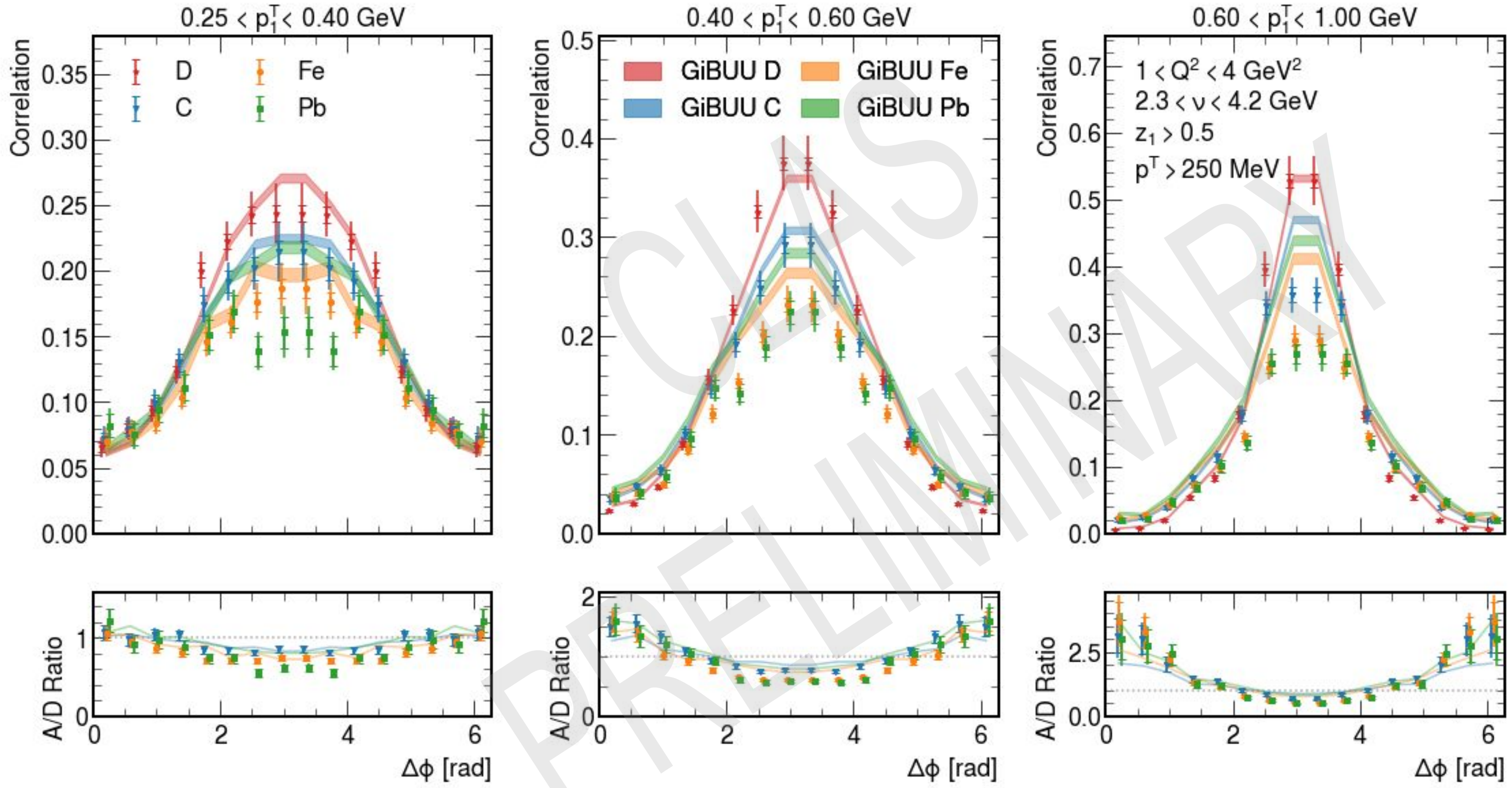
$$Y = \frac{1}{2}\ln\frac{E_h + p_{z,h}}{E_h - p_{z,h}}$$



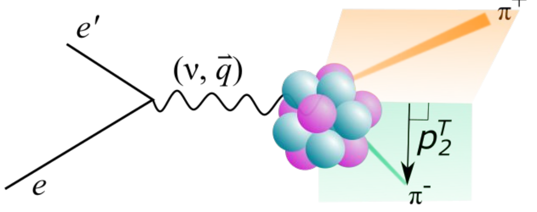
Transverse momentum of leading pion



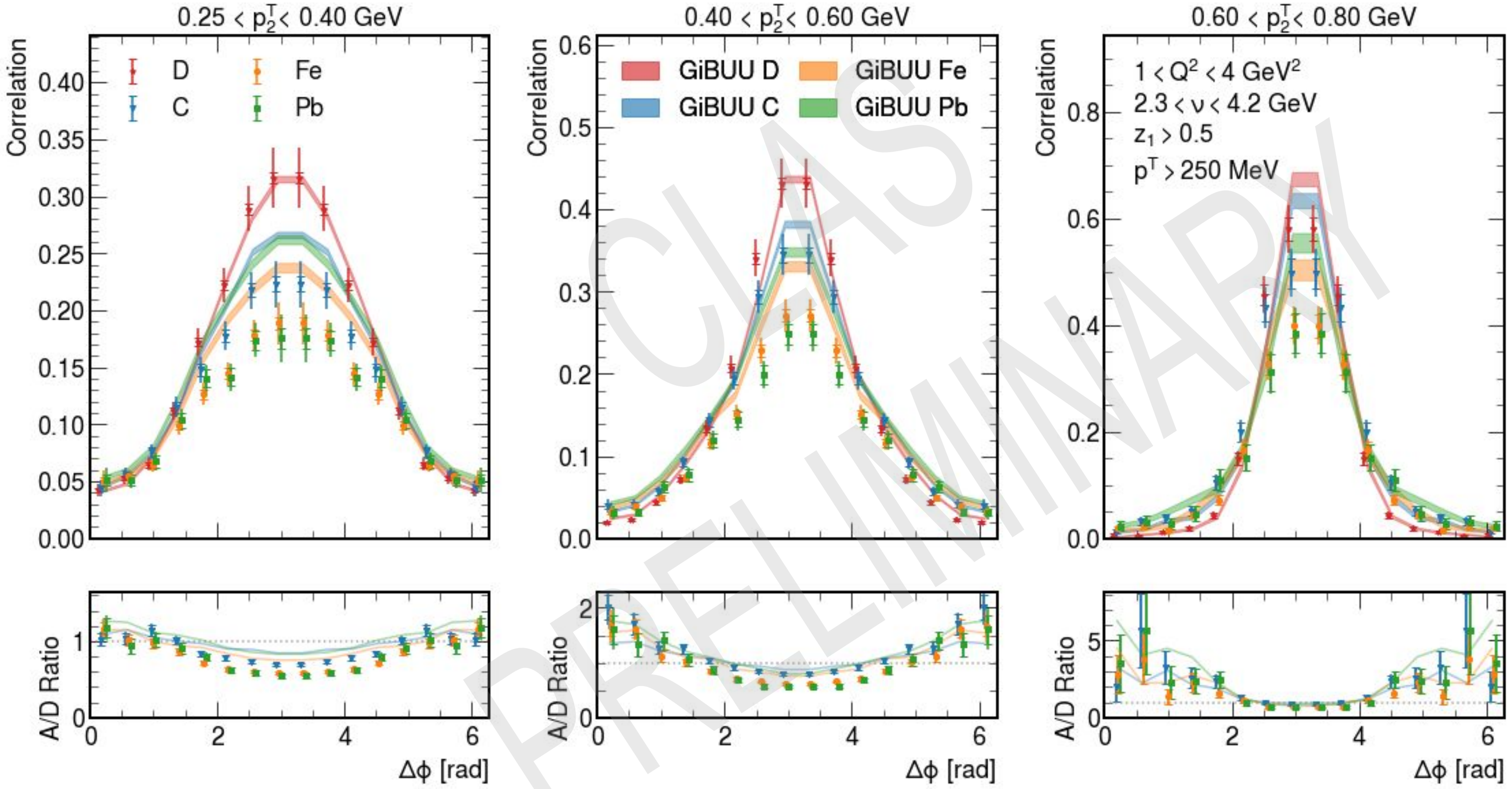
- Narrower correlations with larger p^T_1,



Transverse momentum of sub-leading pion

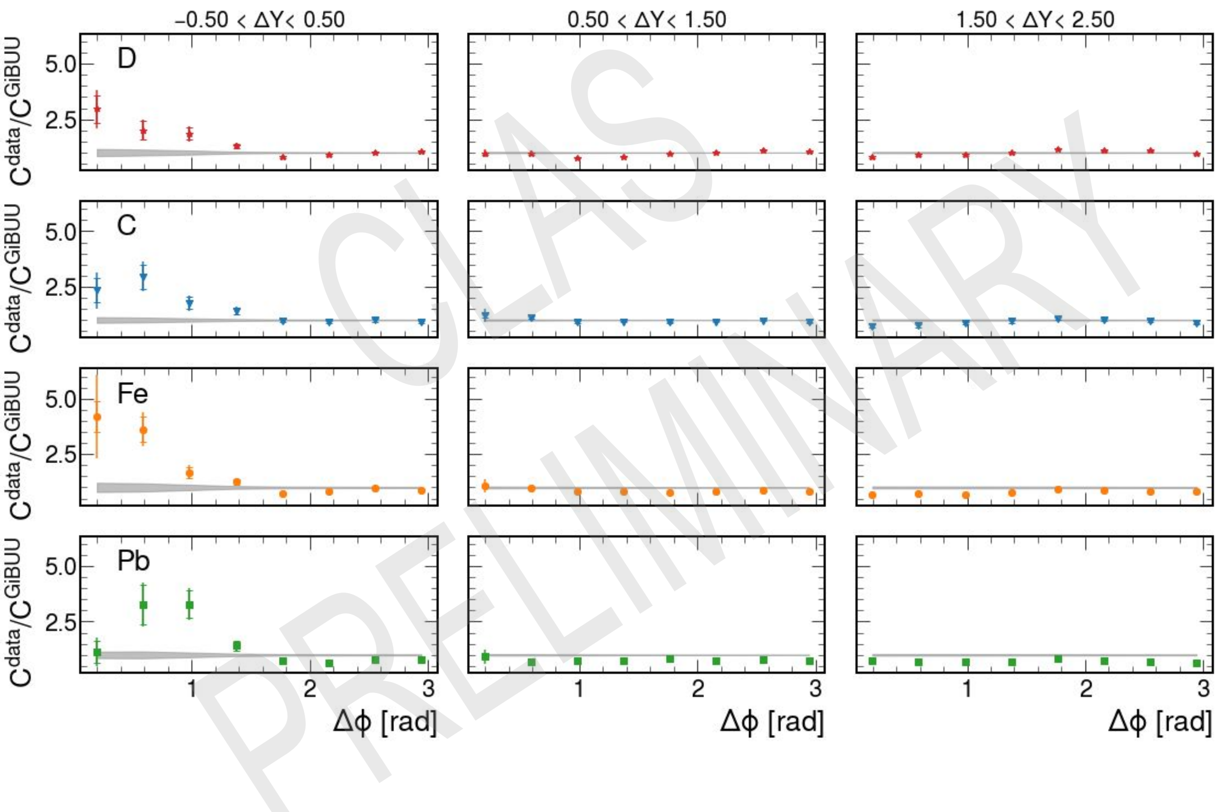


- Narrower correlations with larger $p^T{}_2$ as well.



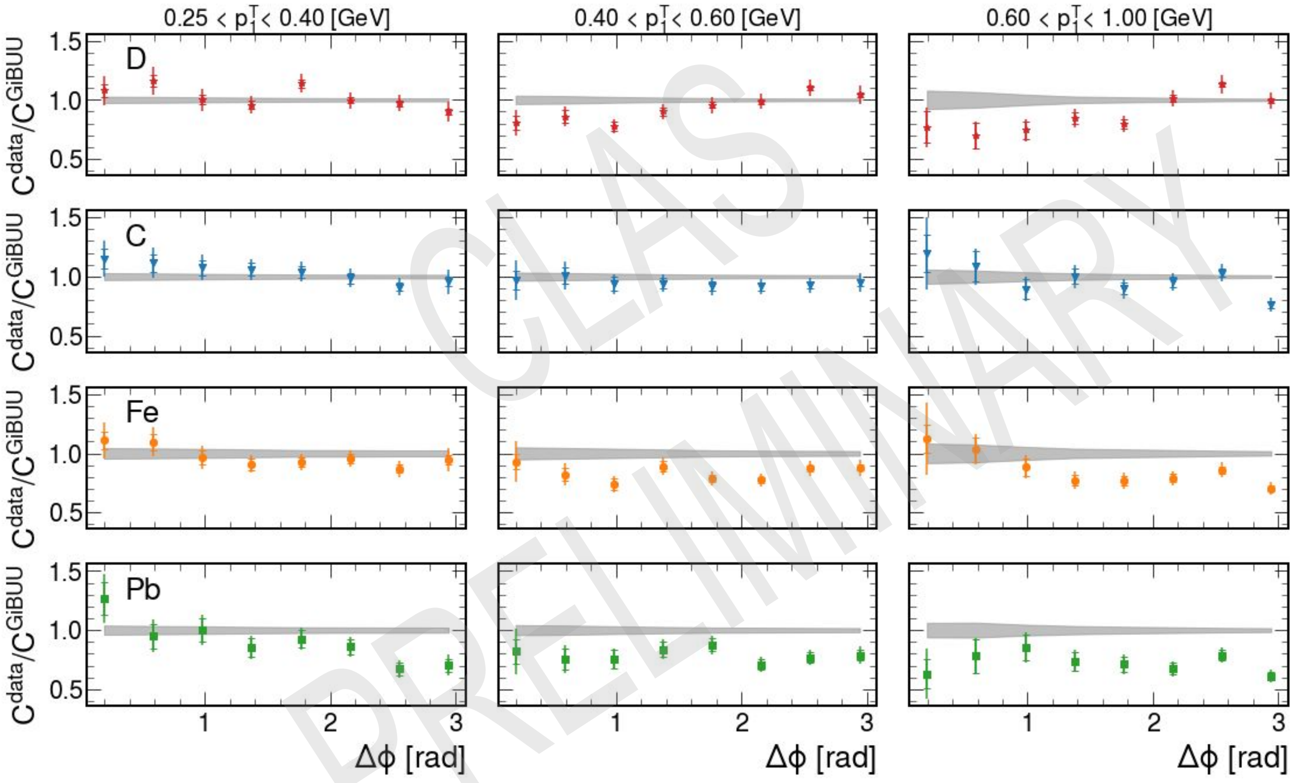
Data/GiBUU ratios: ΔY slices

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



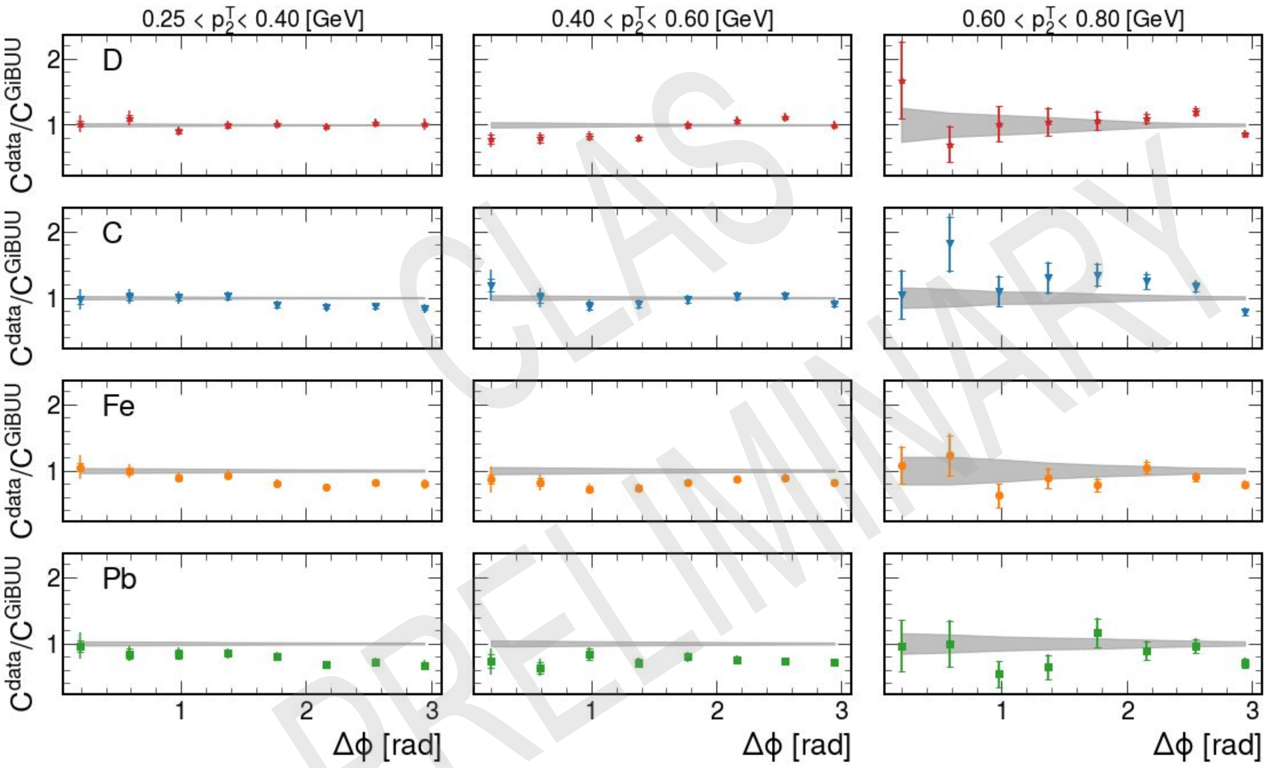
Data/GiBUU ratios: p^T_1 slices

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



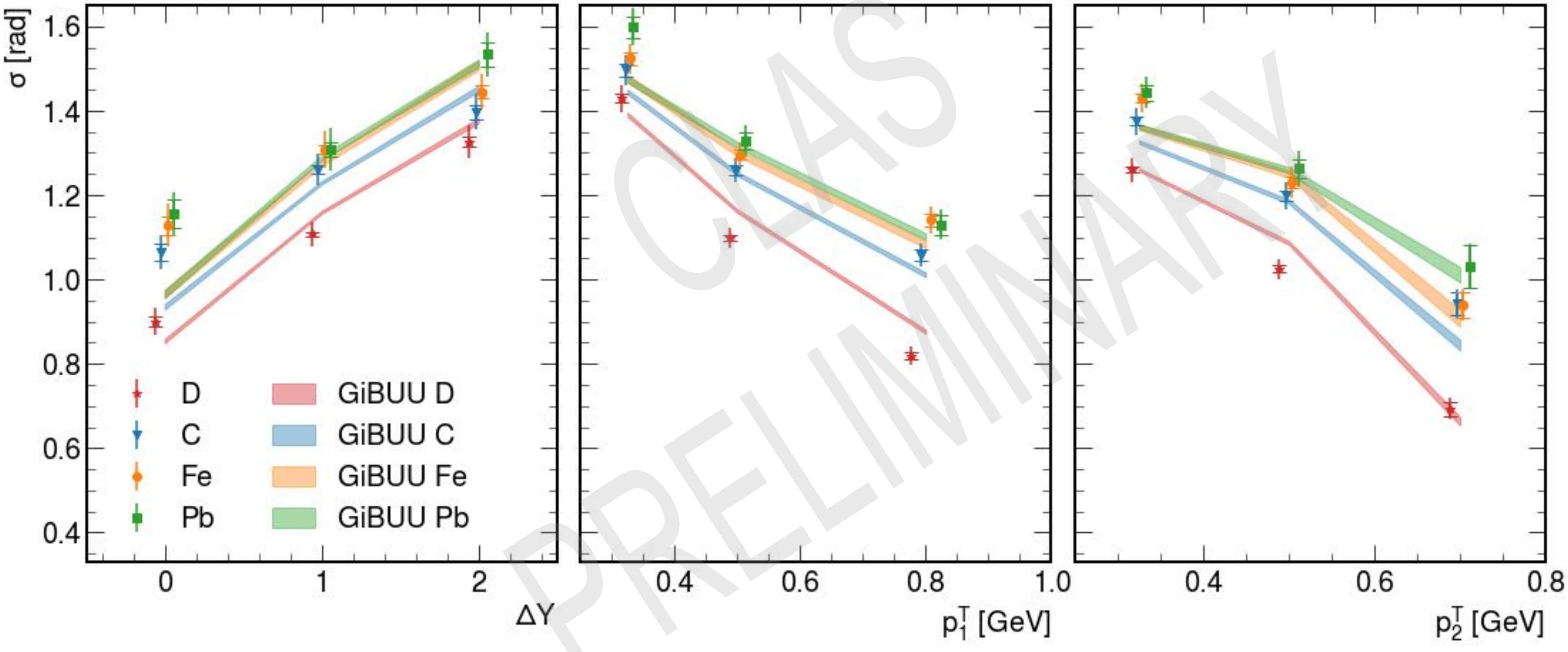
Data/GiBUU ratios: p^T_2 slices

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



Widths of correlation functions (RMS)

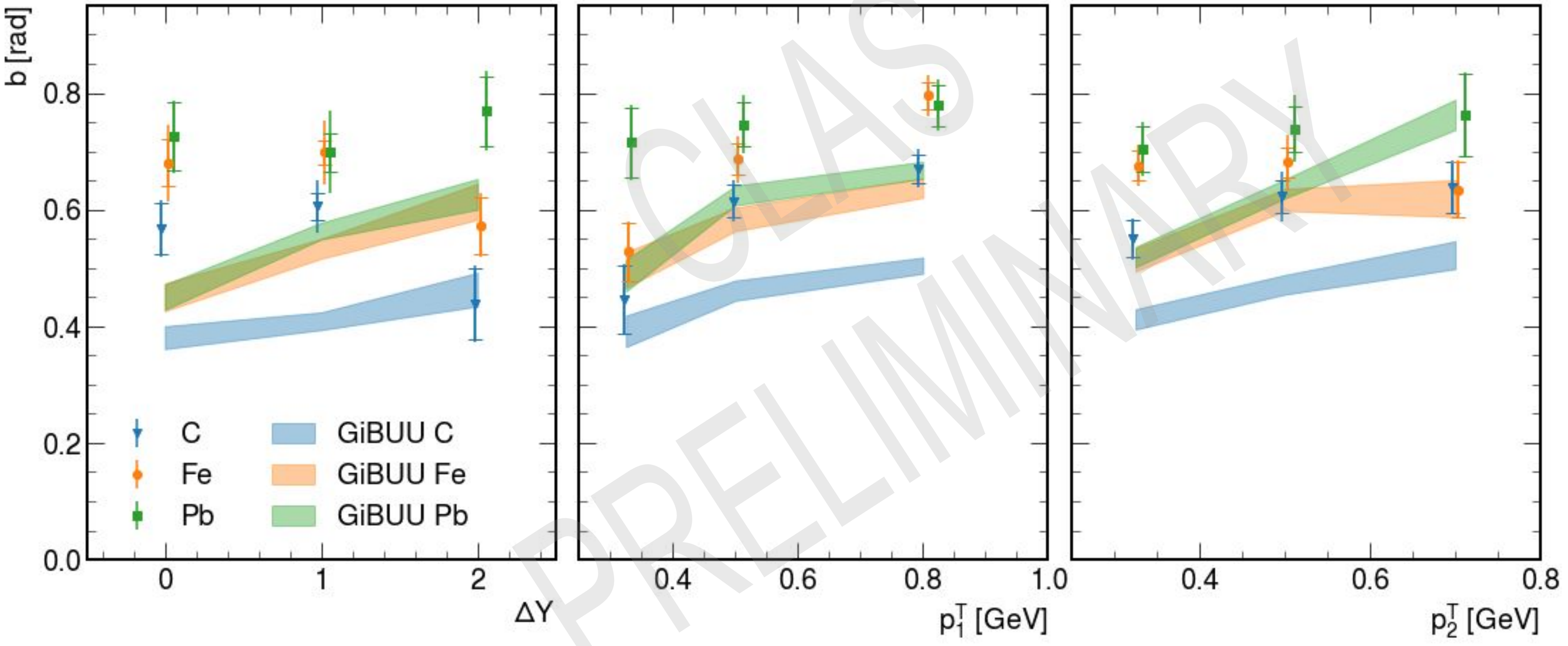
$$\sigma = \sqrt{\frac{\int_0^{2\pi} d\Delta\phi \; C(\Delta\phi)(\Delta\phi - \pi)^2}{\int_0^{2\pi} d\Delta\phi \; C(\Delta\phi)}}$$



Broadening of correlation functions

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

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



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
- 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
- Analysis note under review

Backup slides

Systematics and corrections: Endcap corrections

- Some (about 2%) of the events from the D target come from the Al endcaps.
- Apply corrections

$$C^{D}_{\mathrm{corr}}(\Delta\phi) = \frac{C^{D}_{\mathrm{obs}}(\Delta\phi) - f_{\mathrm{Al}} C_{\mathrm{Al}}(\Delta\phi)}{\int_0^{2\pi} d\Delta\phi \left[C^{D}_{\mathrm{obs}}(\Delta\phi) - f_{\mathrm{Al}} C_{\mathrm{Al}}(\Delta\phi)\right]}$$

  - Correlation function for Al derived from C and Fe.
  - Systematic uncertainty due to difference between C and Fe (Al assumed to be in between them)
- Systematic uncertainty for width determined by applying correction assuming $C_{Al} = C_C$ and $C_{Al}=C_{Fe}$, and taking half the difference

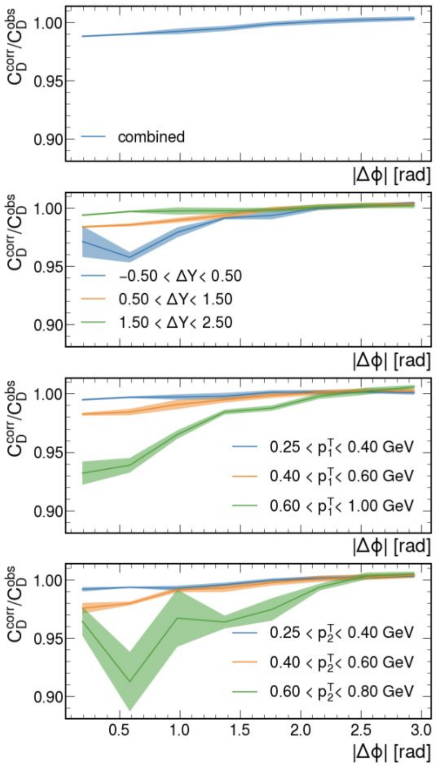


Figure 7.10: Relative corrections to the D data for scattering in the endcaps. Bands represent the values of these corrections ± the systematic uncertainty on the correction.

Systematic uncertainties: Particle Misidentification

- Used deuteron MC (Pythia + detector effects) to estimate contamination rate: protons and kaons misidentified as pions in
- Up to ~17% for one bin, but most are below 1%
- Scale the misidentification rate for nuclear targets using GiBUU calculations: up to 2-3% higher for Pb
- Systematic uncertainty for σ determined by recalculating it with the estimated contamination subtracted from the correlation function. Δσ is the difference between σ calculated with and without this subtraction
- Δb and R2h calculated likewise

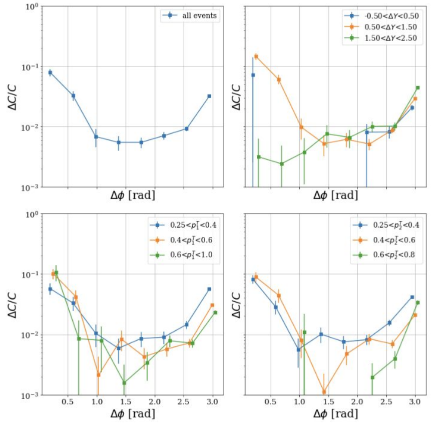


Figure 7.11: Fraction of events with a non-pion misidentified as a pion, as a function of $\Delta\phi$, as determined using the PYTHIA event generator for deuterium, plus detector-effect simulations. The panels represent the unsliced dataset (upper left), the data sliced in ΔY (upper right), p_1^T (lower left) and p_2^T (lower right).

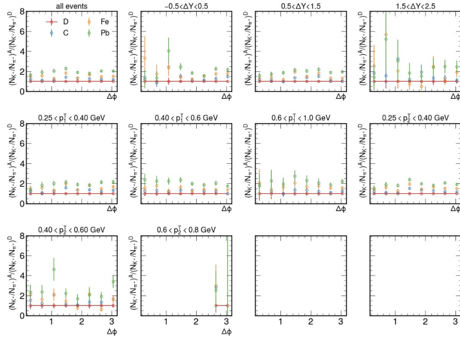
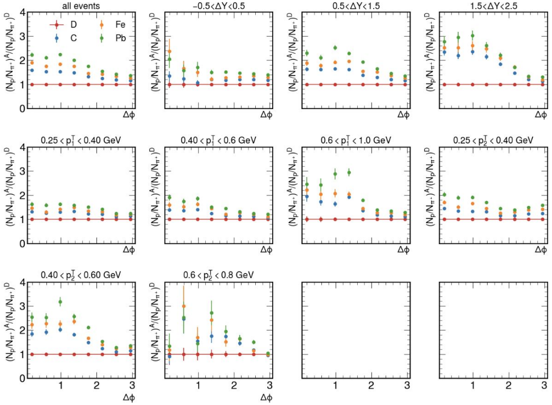


Figure 7.13: Ratio of the number of high-momentum K^+ to that of π^+ for th nuclear targets divided by that of deuterium, as determined usin the GiBUU event generator. Each panel represents the full datase (top left) or a multidimensional bin.



Systematic uncertainties: Event selection

- Repeat analysis with modified cuts on variables
- Take difference from nominal
- Quadrature sum for all modified cuts that have a significant effect or C(Δφ), ie, the cut on the minimum pT for both hadrons
- Same procedure for C, R2h, σ and b

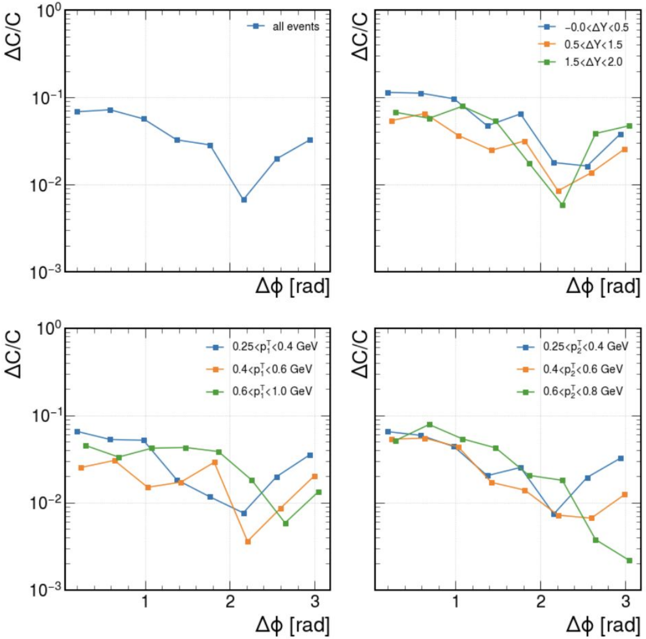
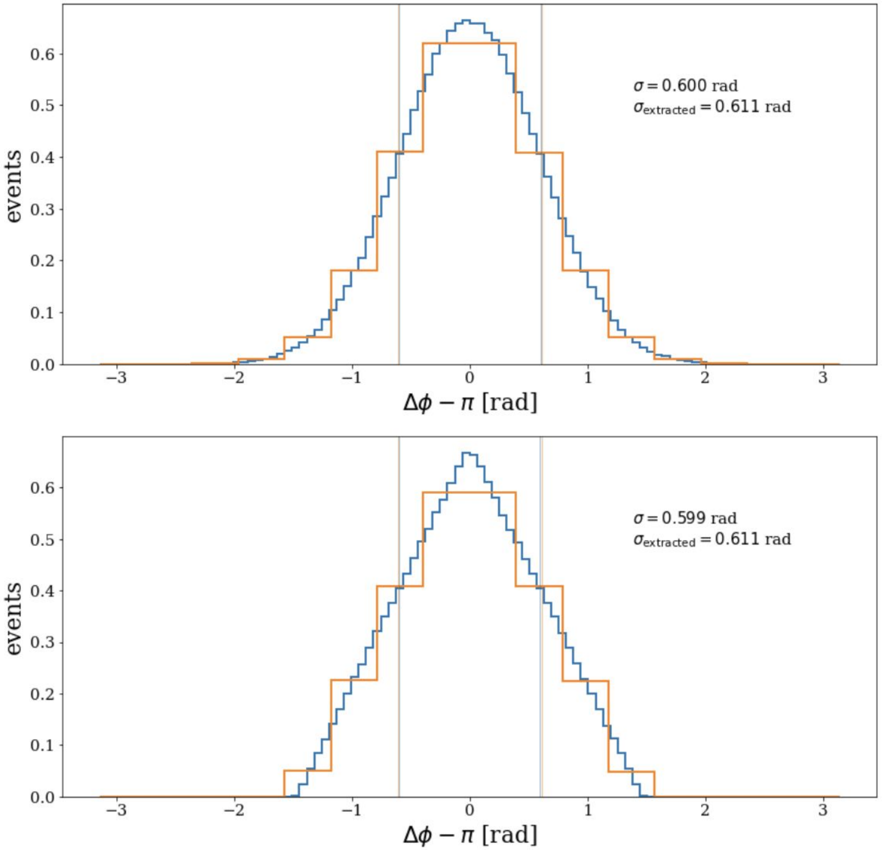


Figure 7.19: Relative systematic uncertainties due to event-selection cuts determined bin-by-bin for the correlation functions.

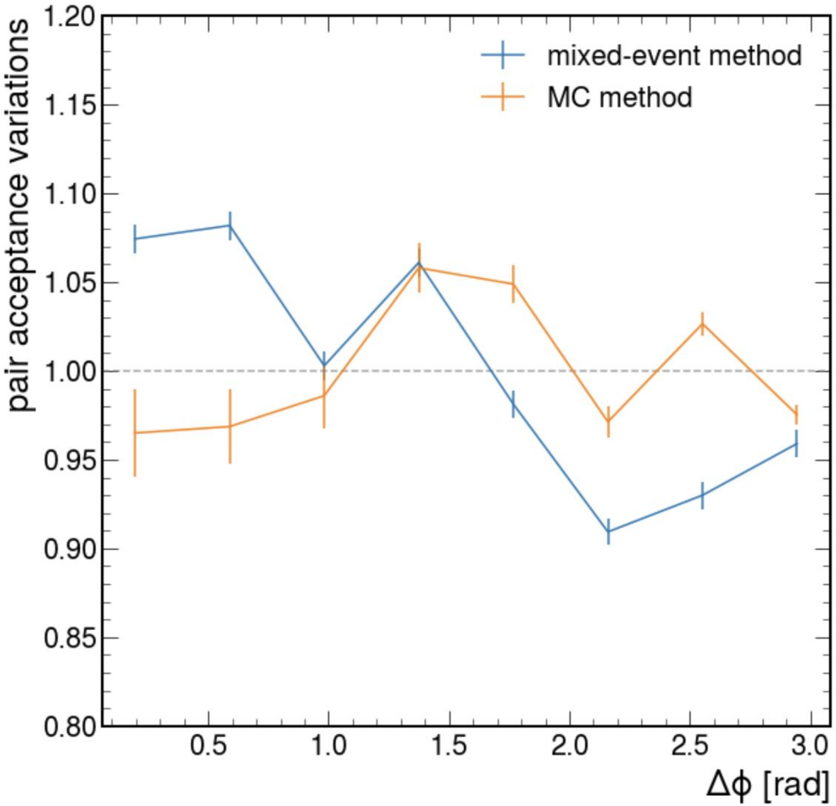
Systematic uncertainties: Finite bin width

- σ calculated from C as a histogram, using Δφ at the center of each bin.
- Effect on the results for σ estimated using toy distributions:
    - Gaussian and triangle shapes.
    - Determined actual σ and binned σ, and took the difference.
- Similar procedure for b using pairs of toy distributions.



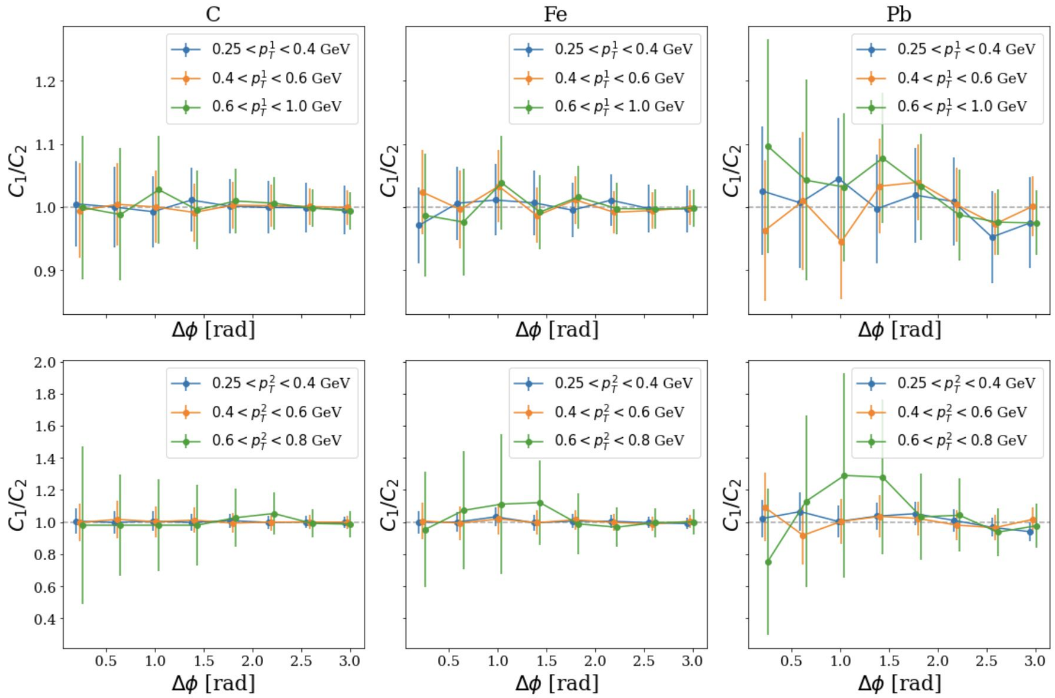
Systematics uncertainties: Pair acceptance effects

- Variations in pair-acceptance and efficiency estimated through two methods:
  - MC: Number of events where all three particles pass cuts on recon divided by total generated in $\Delta\varphi$ bin. Then renormalize.
  - Mixed events: Use leading pion and electron from one event, and the sub-leading pion from another event, and get $\Delta\varphi$ distribution
- We used the RMS value obtained from the second method for systematic uncertainty on C (6.2%)
- For σ and b, we used toy distributions, with each bin scaled randomly by 6.2%



Systematic uncertainties: Coulomb effects

- Conversion of energy from potential to kinetic (or vice versa) as particles exit the nuclei can cause them to change their p_T, putting the event in a different p^T_1 or p^T_2 slice than they would be in otherwise
- Checked if applying corrections changes the result.
  - Since deviations are less than one statistical sigma, no additional systematic uncertainty is added



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.