First Measurement of $\Lambda$ Electroproduction off Nuclei in the Current and Target Fragmentation Regions

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The study of the underlying structure of hadrons suggests a dynamical origin of the strong interactions between the confined color objects, quarks and gluons (partons), the building blocks of nuclei. Given that the description of the nonperturbative transition from partonic degrees of freedom to ordinary hadrons cannot be performed within the perturbative quantum chromodynamics (QCD) or lattice QCD frameworks, pure phenomenological methods are explored to study low-energy phenomena such as the hadronization process [1, 2]. To this end, deep-inelastic electron-nucleon scattering (DIS) has been utilized as a pioneering process on atomic nuclei to access the modified parton distributions, test the hadronization mechanisms, and study color confinement dynamics in the cold nuclear medium [3–5]. In this regime, when the electron emits an energetic virtual-photon (\(\gamma^*\)) that removes the struck quark from the rest of the residual system, it takes a finite time until the reaction products hadronize. These products would, in lepton-nucleus scattering, interact with the surrounding nuclear medium during the formation time, which is approximated at intermediate energies to be of a similar order as nuclear radii [6]. The target nucleus acts then as a femtoscope with unique analyzing power that allows for the extraction of the hadronization time-distance scales. Therefore, the study of scattering off nuclei with different sizes and at various energies probes the space-time evolution of the hadronization mechanism related to the quark propagation and the color field restoration to form regular hadrons [7, 8].

As depicted in Fig. 1, the hadronization process is characterized by two timescales describing its two phases. After the virtual photon hard scattering, during the production time (\(\tau_p\)), the struck quark propagates in the medium as a colored object and thus emits gluons (even in vacuum). This quark then transforms into a colorless object, referred to as a prehadron, which eventually evolves into a fully dressed hadron within the formation time (\(\tau_f\)). The hadronization studies are thus performed to provide information on the dynamics scales of the process, and to constrain the existing models that provide different predictions of its time characteristics either in vacuum or in nuclei [9–13]. In principle, the production and formation mechanisms are the same for both cases.
tron and SIDIS hadron yields produced on a target and corrected for detector acceptance and reconstruction
broadening, $\Delta$ formation. during the color-neutralization stage preceding hadron
to the (pre)hadron elastic or inelastic scattering and/or $R$ efect [7].
correct for the European Muon Collaboration (EMC) ef-
trons originating from corresponding targets to cancel,
Fig. 1. The multiplicity ratio is normalized by DIS elec-
momentum with respect to the virtual-photon direction (see
Fig. 2 top right). This observable carries crucial in-
fication about the interaction of the propagating parton with the surrounding color field in the nucleus.
Several models correlate the $p_T$-broadening with the parton energy loss triggered by the stimulated gluon bremsstrahlung while crossing the medium in the color-
nearalization stage [19, 20]. Based on the perturbative
view of the Lund string model, the propagating quark’s energy loss is predicted to be at a rate comparable to its string constant on the order of 1 GeV/fm [9, 21]. This
effect is believed to be the reason behind the observed jet quenching in heavy-ion collisions at the Relativistic
Heavy Ion Collider and at the Large Hadron Collider, leading to the suppression of large $p_T$ hadron produc-
tion in nucleus-nucleus compared to proton-proton colli-
sions [22, 23].

In this Letter, results on SIDIS production of $\Lambda$ hyper-
ons off nuclei, i.e., $e+ A \to e' + \Lambda + X$, are reported, where $A$ is the heavy nuclear target or deuterium. $X$ is the un-
observed hadronic system, and $\Lambda$ is identified in the final
state through its decay products $\pi^- + p$. The results
represent the first-ever measurement of $\Lambda$ multiplicity ra-
tios and $p_T$-broadening as a function of $z$ and the atomic
mass-number, $A$, for the latter in the current (forward)
fragmentation region, in which the struck (di)quark initi-
ates the hadronization process, and the target (back-
ward) fragmentation region, in which the target remnant
moves reciprocally with regard to the $\gamma^*$ direction under-
going a spectator or target fragmentation. Furthermore,
the current and target fragmentation processes are as-
sumed to have dominant contributions in distinct phase
space regions, which are kinematically separated via the
coverage of the Feynman scaling variable $x_F$ [24, 25].

Previous measurements of $R^A_h$ for various hadrons, mainly mesons and (anti)protons by the HERMES [14–
18] and the CLAS [26, 27] Collaborations have reported
a strong suppression of leading hadrons at high $z$ and a slight enhancement of multiplicity ratios at low $z$ while scanning heavy to light nuclei. This inverted effect for slow (backward) and fast (forward) protons in HERMES
results, the sole baryon study so far, demonstrates the
importance of separating the two regions to properly in-
terpret the data. Approximate separation is possible via
the $z$ dependence of the Feynman variable $x_F$ [28] given
that the current fragmentation (high $z$) is dominated by
positive $x_F$, while the target remnant favors negative $x_F$ [24, 25, 29].

A study of $\Delta p_T^2$ for mesons was also performed by the
HERMES experiment [17], but its finding could not dis-
guish between models predicting an $A^{1/3}$ or $A^{2/3}$ mass dependence [19, 20]. The $\Delta p_T^2$ is expected to increase lin-
early as $A^{1/3}$ if it is proportional to the nuclear radius and thus the crossed path length, $L$, in the nuclear medium,
while an increase as $A^{2/3}$ would indicate a dependence on
partonic energy loss via the prediction that $\frac{dE}{dx} \propto \Delta p_T^2$.
and thus $\Delta E \propto L^2$ [19].

The data presented in this paper were collected during early 2004. An electron beam of 5.014 GeV energy was incident simultaneously on a 2-cm-long liquid-deuterium target (LD2) and a 3-mm-diameter solid target (carbon, iron, or lead). A remotely controlled dual-target system [30] was used to reduce systematic uncertainties and allow high-precision measurements of various experimental observables [27, 31]. The cryogenic and solid targets were located 4 cm apart to minimize the difference in CLAS acceptance, while maintaining the ability to identify event-by-event the target where the interaction occurred via vertex reconstruction [32]. The thickness of each solid target (1.72 mm for C, 0.4 mm for Fe, and 0.14 mm for Pb) was chosen so that all targets including deuterium would have comparable per-nucleon luminosities ($\sim 10^{34}$ cm$^{-2}$s$^{-1}$). The scattered electrons, negative pions, and protons were detected in coincidence using the CLAS spectrometer [33]. The scattered electrons were identified requiring a coincidence between the Cherenkov counter and the electromagnetic calorimeter signals [31], while pions and protons were identified through time-of-flight measurements [31, 32, 34].

The $\Lambda$ hyperons were identified through the reconstructed invariant mass of detected pions and protons (see the first section of the Supplemental Material (SP.1) for more details about the $\Lambda$ identification method [35]).

For each event, several kinematic variables were evaluated including $Q^2$, the virtual photon-nucleon invariant mass squared $W^2$, and the $\gamma^* E_e$ energy fraction $y = \nu/E_e$, where $E_e$ is the incident beam energy. The SIDIS $\Lambda$ events were selected with $Q^2 > 1 \text{ GeV}^2$ to probe the nucleon structure, $W > 2 \text{ GeV}$ to suppress contamination from the resonance region, and $y < 0.85$ to reduce the size of radiative effects on the extracted multiplicity ratios based on the HERMES studies [14–18]. The $(p, \pi^-)$ invariant mass distributions are shown in Fig. 2 left for iron (top) and LD2 (bottom) with all cuts applied. The distributions exhibit a clean $\Lambda$ peak positioned around 1115.7 MeV sitting on a substantial combinatorial background (CB). An advanced data modeling and fitting toolkit RooFit [36] was used along with the event mixing technique to subtract the CB (red dotted curves in Fig. 2 left), which is reconstructed by combining uncorrelated $p$ and $\pi^-$ tracks from different events [37]. The extraction of the background-subtracted $\Lambda$ yields, as well as the $p_T^\Lambda$ means, was performed after weighting their distributions event-by-event with the inverse of the acceptance correction (AC) factors. The latter were evaluated using events generated with the Pythia event generator [38] and processed by the CLAS GEANT3 package [39] to simulate the detector geometrical acceptance, as well as the associated detection and reconstruction efficiencies. Pythia was modified to include nuclear parton distribution functions [40] and Fermi motion based on the Paris potential distribution and realistic many-body calculations [41]. Radiative effects were also included in the simulation using the RadGen code [42] developed to correct lepton-nucleon scattering observables from quantum electrodynamics radiative processes. Small corrections were also applied for other effects related to proton energy loss, scattering angle and momentum distortions, vertex misalignment [32, 34], and LD2 end-cap contamination.

Due to the limited statistics of the $\Lambda$ production channel, the extractions of both multiplicity ratios and $p_T$-broadening results were performed by integrating over all kinematic variables except $z$, which is divided into the six bins shown in Table S2 of the Supplemental Material [35]. Given that the interest in this work is in the $z$ and $A$ dependencies of the observables, the systematic uncertainties were separated into point-to-point ($p2p$), which exhibit some $z$ and $A$ dependencies, and normalization uncertainties, which are kinematics independent. An in-depth study was carried out and the main systematic sources are related to 1) particle identification cuts to identify the three final-state particles, scattered electron, $p$, and $\pi^-$, 2) dual-target vertex corrections, 3) AC multidimensional (6D) map variables and the binning that was chosen based on the comparison of experimental data and simulation, 4) AC weight cuts to suppress artificial spikes due to poor statistics in some AC 6D bins, 5) CB subtraction methods by varying the event mixing uncorrelated

![Figure 2. Left: acceptance-weighted $(p, \pi^-)$ invariant mass distributions for the Fe/LD2 (top/bottom) targets. Blue curves represent the RooFit $\chi^2$ minimization using a simple Breit-Wigner (BW) function for the $\Lambda$ signal and event mixing for the combinatorial background (red dotted curves). The green distributions are the fit results that are integrated to obtain the $\Lambda$ yields. Right: comparison of Fe (red) and LD2 (blue) acceptance-weighted $p_T/\rho_T^\Lambda$ (top/bottom) normalized distributions to their peak height.](image-url)
track combinations and BW shapes utilized in RooFit for $R^A_\Lambda$ while considering CB sideband subtraction for $\Delta p_T^2$, 6) $\Lambda$ mass range for $R^A_\Lambda$, and 7) LD2 end caps and radiative correction procedures. As a result, the total $p_2p$ (normalization) uncertainties vary between 6% to 30% (less than 3%) for the multiplicity ratios of all nuclei with the dominant contributions from the AC and CB subtraction methods (see Table S3 [35]). Similarly, the total $p_2p$ uncertainties vary between 10% (1.4%) and 81% (8.5%) for the nuclear $z$ ($A$) dependence of $p_T$-broadening (see Table S4 (S5) [35]), while the total normalization uncertainty for both dependencies is less than 1%. The largest $p_2p$ $z$-dependent uncertainty, which is associated with the lead target, is still less than the 50% statistical uncertainty as shown in Fig. 4.

The $\Lambda$ multiplicity ratio results are depicted in Fig. 3 along with theoretical calculations from the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model [43]. As expected, $R^A_\Lambda$ manifests an inverted behavior in the two $z$ regions; at high $z$ (see Fig. 3 right), the region in which the current fragmentation dominates, $\Lambda$ baryons exhibit less attenuation in lighter nuclei and greater suppression with $z$, up to 40% in lead and 35% in iron at the highest $z$ bin. However, at low $z$ (see Fig. 3 left) $R^A_\Lambda$ is more enhanced on heavy nuclei as a signature of the significant contribution from the target fragmentation that predominates in this kinematic region. This observation is consistent with the fact that the $\Lambda$ baryons show a significant leading particle effect; i.e., they carry a substantial fraction of the incoming proton momentum [44] and thus large negative $x_F$ (see Fig. S1 [35]) and small $p_T$ relative to the $\gamma^*$ direction [24, 25]. The data are qualitatively described by GiBUU for most of the $z$ range and most of the targets except for the lowest $z$ bin, where approximately a factor of two difference is observed.

Figure 4 contains the $\Lambda$ $p_T$-broadening results as a function of $z$ (left) and $A$ (right) along with theoretical calculations from the GiBUU model [43]. The monotonic increase of broadening with $z$ and the mass-number reflects the interaction of the propagating object with the surrounding color field in the nucleus during the neutralization stage and/or the elastic scattering of the prehadron and the fully formed $\Lambda$ [19, 20]. Such a (pre)hadron interaction, as well as broadening, seems to diminish at the highest $z$ bin. This is an indication of the partonic stage dominance of the hadronization process preceding the (pre)hadron formation, as their elastic scattering in the medium should have led to more broadening as $z$ approaches unity [17, 45]. This trend is in favor of the $A^{1/3}$ dependence of $\Delta p_T^2$ and implies that the production time is within the nuclear medium. Yet, the measured $\Lambda$ hyperon broadening is an order of magnitude greater than that seen in the HERMES meson results [17]. This could be due to the quark-diquark nucleon structure so that the virtual photon, instead of being absorbed by a quark, is absorbed by a diquark. That is to say, the propagating colored diquark has a sizable mass and an extended QCD color field compared to a single quark, leading to more in-medium interactions, and thus an increase of the $\Delta p_T^2$ magnitude [46]. This diquark scattering speculation offers a good explanation of the $R^A_\Lambda$ attenuation with increasing $z$ in the current fragmentation region. While GiBUU has reasonably described HERMES, EMC [6, 47, 48], and CLAS [26, 27] multiplicity ratio measurements, it underestimates our $\Lambda$ $p_T$-broadening results, which could indicate that the an-
Figure 4. Left (right): the $z$ (nuclear radius)-dependent $\Delta p_T^2$ results for the three nuclei (results are horizontally shifted for clarity). The outer error bars are the $p2p$ systematic uncertainties added in quadrature with the statistical uncertainties, while the normalization uncertainties are presented in the inset for the $z$ dependence and found to be less than 1% for the $A$ dependence. The GiBUU model calculations are represented by the colored (left) and shaded (right) bands obtained by interpolating the model points and their statistical uncertainties.

In summary, the first-ever measurement of $\Lambda$ multiplicity ratios and $p_T$-broadening as a function of $z$ and $A$ in the current and target fragmentation regions are reported. Both observables depend strongly on $z$, with an enhancement of $R_A^\Lambda$ at low $z$ and a suppression at high $z$ up to 0.951 $\pm$ 0.125 for carbon, 0.645 $\pm$ 0.164 for iron, and 0.562 $\pm$ 0.219 [50] for lead, and an increase of $p_T$-broadening with $A$ and $z$ except for the last $z$ bin where the broadening starts decreasing due to the partonic stage dominance of the hadronization process. The one order of magnitude larger broadening for this hyperon channel compared to HERMES meson results, as well as the strong suppression of $R_A^\Lambda$ at high $z$, suggests the possibility of a direct scattering off diquark configurations of the nucleon. The multiplicity ratio results are qualitatively described by the GiBUU transport model, however, the model strongly underestimates our $p_T$-broadening results. This finding has the potential to stimulate further experimental and theoretical investigations, constrain existing models such as GiBUU, and open a new era of studies of nucleon and light hyperon structure.

Future higher-luminosity measurements with CLAS12 and an 11 GeV beam energy [51] will study SIDIS production of a variety of mesons and baryons over a wide kinematic range. This is crucial to constrain competing models and boost our understanding of the fragmentation mechanisms that lead to the formation of various hadrons. It would also provide an opportunity to study for the $\Lambda$ SIDIS final states the correlation between kaons and $\Lambda$’s that will presumably be sensitive to the diquark structure in the struck nucleon. The forthcoming experiments with CLAS12, in addition to measurements at the planned Electron Ion Collider [52], have the potential to investigate in great detail the speculated diquark scattering in the current results, which would have a significant impact on our understanding of nucleon and baryon structure.

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SUPPLEMENTAL MATERIAL

This appendix contains supplementary information about the \( \Lambda \) identification method in SP.1, the acceptance correction details related to the multidimensional (6D) map variables and binning, weight definition and cut, and its application procedure in SP.2, a summary of the contributions of systematic effects to the total point-to-point uncertainty budget in SP.3, and the reported results in the last two figures of this manuscript, Figs. 3 and 4, as well as two supporting figures, Figs. S1 and S2, in SP.4. In Table S6, the \( z \)-binned multiplicity ratios are given for all nuclei, while Table S7 (Table S8) contains the transverse momentum broadening as a function of \( z \) for all nuclei.

SP.1 Lambda Identification

In the sample of reconstructed SIDIS events originating from either the liquid or solid target, one scattered \( e^- \) and at least one \( \pi^- \) and \( p \), the decay products of the \( \Lambda \), were required. To reconstruct the \( z \)-binned (\( \pi^- \), \( p \)) invariant mass spectrum for each target, the 4-vector energy-momentum (\( P^\mu = (E, \vec{p}_x, \vec{p}_y, p_z) \)) of all identified negatively charged pions and protons were combined event-by-event as

\[
P_\Lambda = P_p + P_{\pi^-},
\]

(S1)

where \( P_\Lambda \), \( P_p \), and \( P_{\pi^-} \) are the 4-vector energy-momentum of the \( \Lambda \) candidates, protons, and \( \pi^- \)'s, respectively. Figure 2 left shows the acceptance-weighted invariant mass from solid (top) and liquid (bottom) targets in which the \( \Lambda \) peak sits on a huge combinatorial background (red dotted curves) that is subtracted using RooFit to extract the pure \( \Lambda \) yields and thus obtain the presented multiplicity ratios in Fig. 3.

SP.2 Acceptance Correction

The adopted acceptance correction for this analysis is based on a bin-by-bin correction method. Its main advantage is that it should be, in principle, independent of the model used in the Monte-Carlo (MC) event generator if the chosen bins are infinitely small. This is very important for this channel since it is not expected that the employed model in Pythia would be realistic enough to perfectly reproduce the data. Based on a comparison between MC and experimental data, the chosen AC six dimensional (6D) map variables and binning are summarized in Tables S1- S2.

| Variables | Range             | Number of bins | Bin width |
|-----------|------------------|----------------|-----------|
| \( W \) [GeV] | 2.00 - 2.80      | 2              | 0.4       |
| \( \nu \) | 2.25 - 4.25      | 3              | 0.6       |
| \( \phi_{\pi^-} \) [deg] | 0.0 - 360.0      | 2              | 180       |
| \( \phi_{e\Lambda} \) [deg] | 0.0 - 360.0      | 3              | 120       |
| \( p_\Lambda \) [GeV] | 0.10 - 4.25      | 3              | 1.383     |
| \( z \) | 0.28 - 1.00      | 6              | see Table S2 |
| Total    |                  | 648            |           |

Table S1. Binning for the AC map, where \( \nu \), \( W \), and \( z \) were already defined, \( \phi_{\pi^-} \) is the \( \pi^- \) azimuthal decay angle in the \( \Lambda \) rest frame, \( \phi_{e\Lambda} \) is the angle between the leptonic and hadronic planes, and \( p_\Lambda \) is the \( \Lambda \) momentum. Table S2 shows the \( z \) bins used as reported in Table S6.

| \( z \)-bin # | 1  | 2  | 3  | 4  | 5  | 6  |
|---------------|----|----|----|----|----|----|
| \( z_{min} \) | 0.28 | 0.38 | 0.44 | 0.51 | 0.60 | 0.75 |
| \( z_{max} \) | 0.38 | 0.44 | 0.51 | 0.60 | 0.75 | 1.00 |

Table S2. The \( z \) bins used in this analysis.

The acceptance correction factors are defined for each 6D bin \( k = (W, \nu, p_\Lambda, \phi_{\pi^-}, \phi_{e\Lambda}, z) \) as

\[
AC_k = \frac{N_{acc}(W, \nu, p_\Lambda, \phi_{\pi^-}, \phi_{e\Lambda}, z)}{N_{gen}(W, \nu, p_\Lambda, \phi_{\pi^-}, \phi_{e\Lambda}, z)},
\]

(S2)
where $N_{\text{gen}}(W, \nu, p_A, \phi_{\pi^-}, \phi_{e\Lambda}, z)$ and $N_{\text{acc}}(W, \nu, p_A, \phi_{\pi^-}, \phi_{e\Lambda}, z)$ are, respectively, the number of generated and accepted events in each bin $k$. Once these AC coefficients were computed, the data were corrected event-by-event by a weight $\omega_k = 1/AC_k$, which depends on the bin $k$ to which it belongs. It should be noted that if some 6D AC bins have very small correction factors due to their poor statistics, an artificially large weight would be attributed to those bins that would lead to spikes in the weighted distributions. To avoid this problem, the following weight cut was adopted to minimize this effect on the weighted distributions:

$$60 < \omega_k \leq 2400.$$  \hfill (S3)

Furthermore, the effect of this weight cut was estimated and applied as a global correction factor, $f_\omega$, to the extracted results. This estimation was done by weighting the MC accepted $N_{\text{acc}}$ events and comparing their sum, $\sum \omega N_{\text{acc}}$, to the generated ones as

$$f_\omega = \frac{\sum \omega N_{\text{acc}}}{N_{\text{gen}}}.$$  \hfill (S4)

This $N_{\text{acc}}$ weighted sum is typically equal to the generated events without the weight cut, however, it is slightly less once applied, leading to various $f_\omega$ corrections for each $z$-binned multiplicity ratio result as the $p_T$-broadening means are insensitive to this correction.

**SP.3 Systematic Uncertainties Budget**  This section contains the contribution of various systematic effects to the reported total point-to-point systematic uncertainty budget for the $\Lambda$ multiplicity ratios of all nuclei in Table S3 and the corresponding $z$ ($A$)-dependence of $p_T$-broadening in Table S4 (S5).

**SP.4 Tabulated Multiplicity Ratio and $p_T$-broadening Results**  This section contains the reported results in the last two figures of this manuscript, Figs. 3 and 4, detailed in Table S6 for all nuclei $z$-binned multiplicity ratios, and Table S7 (Table S8) for all nuclei $z$-binned ($A$-dependent) transverse momentum broadening. In addition, the correlation between $z$ and the Feynman variable $x_F$ is illustrated in Fig. S1 to support the discussion related to the separation between forward and backward fragmentation regions. Furthermore, the $z$-binned distributions, as well as AC-weighted averages, of the Bjorken scaling variable $x_B$ are shown in Fig. S2 and Table S9 to illustrate our kinematical coverage for any theoretical calculations aiming to describe our data.

![Figure S1. $z$ vs. $x_F$, where the horizontal dashed line around values of $z$ greater than $\sim 0.55$ depicts the discussed separation between forward and backward fragmentation regions suggested by the sign change of $x_F$ (vertical dashed line).](image-url)
Table S3. Multiplicity ratio systematic effects and their contributions for the $z$ bins shown in Table S2.

| Systematic Effect                              | $z$ bin | Carbon | Iron | Lead |
|-----------------------------------------------|---------|--------|------|------|
|                                               | $z-1$  | $z-2$  | $z-3$ | $z-4$ | $z-5$ | $z-6$ | $z-1$ | $z-2$ | $z-3$ | $z-4$ | $z-5$ | $z-6$ |
| Particle identification cuts                   | 0.69    | 4.24   | 7.24  | 1.53  | 3.16  | 0.00  | 0.00  | 0.95  | 4.34  | 0.87  | 3.17  | 4.45  |
| Vertex corrections                              | 0.28    | 0.00   | 0.04  | 0.22  | 0.22  | 0.54  | 1.04  | 1.28  | 0.56  | 0.08  | 0.00  | 0.13  |
| AC 6D map variables & binning                  | 3.28    | 0.00   | 0.00  | 6.69  | 9.97  | 9.17  | 2.33  | 6.83  | 4.80  | 0.00  | 6.42  | 5.90  | 4.93  |
| AC weight cuts                                  | 0.00    | 0.00   | 10.70 | 0.70  | 0.00  | 0.00  | 0.00  | 0.00  | 9.17  | 1.86  | 0.00  | 0.00  | 5.17  | 0.00  | 8.64  | 12.16 | 0.00  | 0.00  |
| CB uncorrelated-tracks combinations             | 1.80    | 0.16   | 0.37  | 0.27  | 0.53  | 0.00  | 1.14  | 0.14  | 0.20  | 0.00  | 0.36  | 0.23  | 1.79  | 2.04  | 0.96  | 0.13  | 0.00  | 0.28  |
| Breit-Weigner shapes                            | 7.55    | 10.80  | 25.75 | 5.13  | 8.69  | 5.77  | 20.54 | 16.37 | 13.40 | 1.26  | 0.46  | 5.27  | 5.77  | 12.02 | 15.71 | 4.92  | 10.85 | 9.52  |
| A mass-range                                    | 2.10    | 1.11   | 0.00  | 0.86  | 1.87  | 2.89  | 2.52  | 1.52  | 0.43  | 0.00  | 1.35  | 2.39  | 2.24  | 1.24  | 0.00  | 0.65  | 1.69  | 2.72  |
| LD2 endcaps                                     | 0.06    | 0.00   | 0.06  | 0.09  | 0.11  | 0.13  | 0.03  | 0.00  | 0.06  | 0.08  | 0.10  | 0.12  | 0.07  | 0.00  | 0.05  | 0.07  | 0.09  | 0.13  |
| Radiative correction                            | 0.00    | 2.08   | 1.26  | 3.18  | 1.53  | 0.94  | 1.30  | 1.14  | 0.29  | 0.00  | 0.95  | 0.21  | 0.13  | 0.00  | 0.81  | 1.12  | 0.58  | 1.90  |
| Total                                          | 8.71    | 11.84  | 29.61 | 11.81 | 13.25 | 6.93  | 21.86 | 17.19 | 16.82 | 6.86  | 6.92  | 8.81  | 13.41 | 12.67 | 21.58 | 15.36 | 15.21 | 14.20 |
Table S4. Transverse momentum broadening systematic effects and their contributions for the z bins shown in Table S2.

| Systematic Effect                  | z bin Point-to-point Systematic Uncertainty (%) |
|------------------------------------|-----------------------------------------------|
|                                    | Carbon | Iron | Lead | Carbon | Iron | Lead | Carbon | Iron | Lead | Carbon | Iron | Lead |
| Particle identification cuts       | 7.14   | 0.00 | 3.77 | 1.77   | 0.47 | 6.03 | 1.05   | 8.19 | 4.97 | 0.00   | 0.82 | 0.87 |
| Vertex Corrections                 | 6.63   | 8.99 | 4.62 | 1.02   | 0.00 | 3.99 | 2.57   | 2.54 | 0.00 | 0.33   | 0.33 | 0.67 |
| AC 6D map variables & binning     | 4.77   | 6.95 | 6.02 | 0.00   | 8.91 | 5.49 | 6.36   | 9.72 | 3.05 | 14.85  | 0.00 | 2.20 |
| AC weight cuts                    | 1.83   | 0.47 | 18.23| 6.74   | 0.00 | 0.09 | 0.00   | 0.31 | 13.77| 0.00   | 0.02 | 0.12 |
| CB sideband subtraction           | 31.84  | 0.0  | 2.1  | 8.81   | 0.88 | 3.79 | 4.34   | 2.36 | 0.0  | 1.67   | 7.58 | 20.32 |
| Radiative correction              | 3.87   | 0.24 | 0.00 | 0.03   | 0.00 | 0.19 | 0.18   | 0.28 | 0.32 | 0.54   | 0.00 | 0.12 |
| Total                             | 33.88  | 11.38| 11.28| 8.96   | 9.84 | 8.19 | 13.18  | 14.96| 15.04| 7.63   | 20.46| 10.89 |

Table S5. A-dependent transverse momentum broadening systematic effects and their contributions.

| Systematic effect                  | Point-to-point Systematic Uncertainty (%) |
|------------------------------------|-----------------------------------------------|
|                                    | Carbon | Iron | Lead |
| Particle identification cuts       | 4.69   | 1.35 | 0.00 |
| Vertex Corrections                 | 2.70   | 0.00 | 0.38 |
| AC 6D map variables & binning     | 0.57   | 0.00 | 2.21 |
| AC weight cuts                    | 3.40   | 0.00 | 7.07 |
| CB sideband subtraction           | 5.52   | 0.0  | 2.87 |
| Radiative correction              | 0.04   | 0.17 | 0.00 |
| Total                             | 8.46   | 1.36 | 7.96 |
Table S6. Measured $\Lambda$ $z$-binned multiplicity ratios for all nuclei along with their total statistical and systematic (point-to-point and normalization uncertainties depicted in Fig. 3 added in quadrature) uncertainties.

| $z$ bin   | $R^A_\Lambda$ ± Statistical ± Systematical Uncertainties | Carbon | Iron | Lead |
|-----------|----------------------------------------------------------|--------|------|------|
| 0.28 - 0.38 | 3.4256 ± 0.5319 ± 0.3004 | 5.7536 ± 0.5681 ± 1.2661 | 7.2363 ± 0.9997 ± 0.9893 |
| 0.38 - 0.44 | 1.3447 ± 0.1603 ± 0.1628 | 1.9382 ± 0.1769 ± 0.3629 | 2.6378 ± 0.3405 ± 0.3863 |
| 0.44 - 0.51 | 1.1084 ± 0.1205 ± 0.3299 | 2.0100 ± 0.1735 ± 0.3674 | 2.1293 ± 0.3405 ± 0.3863 |
| 0.51 - 0.60 | 1.1498 ± 0.0883 ± 0.1400 | 1.2126 ± 0.0823 ± 0.1663 | 1.1857 ± 0.1057 ± 0.2659 |
| 0.60 - 0.75 | 1.1174 ± 0.0756 ± 0.1519 | 0.9660 ± 0.0617 ± 0.1588 | 0.8910 ± 0.0759 ± 0.2364 |
| 0.75 - 1.00 | 0.9506 ± 0.1011 ± 0.0741 | 0.6450 ± 0.0529 ± 0.1549 | 0.5622 ± 0.0621 ± 0.2096 |

Table S7. Measured $\Lambda$ $z$-binned $p_T$-broadening results for all nuclei with their total statistical and systematic (point-to-point and normalization uncertainties depicted in Fig. 4 left added in quadrature) uncertainties.

| $z$ bin   | $\Delta p_T^2$ (GeV$^2$) ± Statistical ± Systematical Uncertainties | Carbon | Iron | Lead |
|-----------|-----------------------------------------------------------------|--------|------|------|
| 0.28 - 0.38 | 0.0003 ± 0.0143 ± 0.0015 | 0.0112 ± 0.0127 ± 0.0015 | -0.0072 ± 0.0151 ± 0.0060 |
| 0.38 - 0.44 | 0.0259 ± 0.0160 ± 0.0033 | 0.0422 ± 0.0140 ± 0.0057 | 0.0592 ± 0.0171 ± 0.0071 |
| 0.44 - 0.51 | 0.0648 ± 0.0174 ± 0.0132 | 0.0894 ± 0.0147 ± 0.0134 | 0.0613 ± 0.0174 ± 0.0144 |
| 0.51 - 0.60 | 0.1317 ± 0.0165 ± 0.0149 | 0.2120 ± 0.0168 ± 0.0319 | 0.2007 ± 0.0211 ± 0.0483 |
| 0.60 - 0.75 | 0.1879 ± 0.0225 ± 0.0169 | 0.2591 ± 0.0218 ± 0.0198 | 0.3140 ± 0.0295 ± 0.0334 |
| 0.75 - 1.00 | 0.1145 ± 0.0157 ± 0.0114 | 0.1381 ± 0.0149 ± 0.0283 | 0.1788 ± 0.0209 ± 0.0250 |

Table S8. Measured $\Lambda$ $A$-dependent $p_T$-broadening results for all nuclei along with their total statistical and systematic (point-to-point and normalization uncertainties depicted in Fig. 4 right added in quadrature) uncertainties.

| $A$    | $\Delta p_T^2$ (GeV$^2$) ± Statistical ± Systematical Uncertainties |
|--------|------------------------------------------------------------------|
| Carbon | 0.0952 ± 0.0272 ± 0.0082 |
| Iron  | 0.1404 ± 0.0376 ± 0.0024 |
| Lead  | 0.1823 ± 0.0451 ± 0.0146 |

Table S9. $z$-binned $x_B$ AC-weighted averages for all nuclei.

| $z$ bin   | $x_B$ AC-weighted Average | LD2 | Carbon | Iron | Lead |
|-----------|---------------------------|-----|--------|------|------|
| 0.28 - 0.38 | 0.2176                    | 0.2395 | 0.2401 | 0.2391 |
| 0.38 - 0.44 | 0.2529                    | 0.2574 | 0.2623 | 0.2551 |
| 0.44 - 0.51 | 0.2585                    | 0.2665 | 0.2701 | 0.2724 |
| 0.51 - 0.60 | 0.2661                    | 0.2699 | 0.2697 | 0.2703 |
| 0.60 - 0.75 | 0.2756                    | 0.2648 | 0.2667 | 0.2646 |
| 0.75 - 1.00 | 0.2921                    | 0.2858 | 0.2821 | 0.2817 |
Figure S2. Comparison of the $z$-binned Fe (red) and LD2 (blue) normalized acceptance-weighted $x_B$ distributions for the depicted $z$ bins that are defined in Table S2.