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Observation of impact parameter dependent modifications of nuclear parton distributions in photonuclear Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ATLAS detector

The ATLAS Collaboration

High-energy photonuclear ($\gamma + A$) scattering in ultra-peripheral heavy-ion collisions provides a unique probe of nuclear structure. This Letter studies the dependence of $\gamma + A$ jet production in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV on the presence of forward neutron emission from either nucleus. The data was taken in 2018 with the ATLAS detector at the LHC and corresponds to an integrated luminosity of 1.72 nb^{-1}. The kinematics of the hard $\gamma + A$ processes, expressed via the particle-level photon (z_{-}) or nuclear parton (x_{+}) momentum fractions, are determined from $R = 0.4$ jets reconstructed using the anti-k_t algorithm. At lower z_{-}, where the non-diffractive component dominates, the nuclear parton distribution can be cleanly probed in collisions that leave the struck nucleus essentially intact. Such collisions are expected to probe larger impact parameters (b_{A}) within the target. The shape of the $\gamma + A$ cross-section as a function of x_{+} in such collisions is found to differ from that in $\gamma + A$ collisions accompanied by forward neutron emission, with an observed significance of 6.0σ. These results are consistent at large x_{+} with large b_{A} collisions exhibiting no modifications to the parton distributions that are usually observed in hard scattering processes involving nuclei, relative to collisions with smaller b_{A}. Thus, these measurements provide an experimental observation that the modifications to nuclear parton distributions vary with impact parameter.

In recent years, there has been significant interest in nuclear parton distribution functions (nPDFs) and their modifications relative to free nucleon distributions. This interest is driven in part by the heavy-ion programs at the Relativistic Heavy Ion Collider and Large Hadron Collider, in which the study of hard-scattering processes is a crucial component. The possibility that nPDF modifications may depend on the impact parameter relative to the center of the struck nucleus (b_{A}) has long been considered [1, 2], although nearly all existing fits neglect any such dependence. If present, this effect would imply that peripheral (large b_{A}) collisions probe different nPDFs than inclusive collisions.

Descriptions of the suppression of nPDFs at low x (shadowing) typically involve multiple scattering, which would necessarily imply a dependence on b_{A} [3]. Also, recent interpretations of the suppressed nPDF at larger x, the "EMC" effect [4], in terms of short-range correlations (SRCs) [5, 6] might suggest a dependence on b_{A} due to variations in the nuclear density and presence of a neutron skin in large nuclei [7]. The b_{A}-dependent nPDFs are also related to the Fourier transform of a special case of the nuclear Generalized Parton Distributions (nGPDs) [1]. These distributions connect inclusive measurements of nPDFs to exclusive vector meson photoproduction results [8–10] that probe the nGPD [11]. While several experimental probes of the b_{A}-dependence of nPDFs have been proposed [12–15], none have yet succeeded in demonstrating or directly constraining this dependence.

ATLAS has performed several measurements [16–18] of inclusive photonuclear ($\gamma + A$) scattering in ultra-peripheral collisions (UPCs), where the nucleus-nucleus impact parameter (b_{AA}) is greater than twice the nuclear radius, so that only photon-induced processes contribute. A recent ATLAS measurement [18] studied $\gamma + A \longrightarrow$ jets production in UPCs, where events are characterized by the number of neutrons emitted from each nucleus, with Xn implying at least one neutron and $0n$ indicating no emitted neutrons. Photonuclear collisions typically have a $0nXn$ topology (panel (a) of Figure 1), as the photons are usually emitted coherently by the source nucleus, which is left un-excited [19]. Conversely, the hard scattering process has a very high probability to excite the struck nucleus, causing the emission of one or more neutrons.

The b_{A} dependence of $\gamma + A$ processes can be characterized using the number of neutrons emitted from the struck nucleus. The relationship between b_{A} and the number of emitted neutrons depends on both the physics of the scattering process and on the de-excitation cascade of the resulting excited nucleus [20–22]. However, on general grounds, a lower number of emitted neutrons suggests photonuclear collisions at larger b_{A}. Thus, the class of collisions with no forward neutrons (panel (b) of Figure 1) would be expected to probe large b_{A}. Such collisions, having a $0n0n$ topology, necessarily involve either a very peripheral collision or one that does not sufficiently excite the struck nucleus to induce emission of recoil or evaporation neutrons. A potential background to the photonuclear process arises from diffractive photonuclear processes involving coherent pomeron ($\boldsymbol{I\!P}$) emission by the struck nucleus ($\gamma + \boldsymbol{I\!P}$) that leaves it intact [23]. These processes are interesting in their own right and have been studied comprehensively in $\gamma + p$ collisions at HERA [24–27].

Photonuclear hard-scattering processes in UPCs may also be accompanied by additional soft photon exchanges which cause electromagnetic dissociation (EMD) and subsequent neutron emission from one or both nuclei in a direction un-correlated with any features of the central event [28, 29]. The probability for additional EMD increases with decreasing b_{AA} [8, 30, 31] so that the presence or absence of "extra" neutrons, for example in the direction of the photon-emitting nucleus in $\gamma + A$, provides indirect sensitivity to b_{A} (see Ref. [11] for a quantitative assessment). Measurements presented in Ref. [32] indicate that the rate for additional EMD of the photon-emitting nucleus in $0n0n$ collisions is lower than that in $0nXn$ collisions. This observation provides additional, independent evidence supporting the claim that $0n0n$ $\gamma + A$ collisions probe larger b_{A} than $0nXn$ collisions.

This Letter presents measurements of $\gamma + A \longrightarrow$ jets scattering in Pb+Pb UPCs at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with no forward neutrons, and thus, a $0n0n$ topology. They are compared to additional measurements of $\gamma + A \longrightarrow$ jets processes in $0nXn$ events with otherwise identical selections. At forward jet rapidity, the non-diffractive contribution to the $0n0n$ cross-section can be cleanly selected using rapidity gap requirements in a kinematic region where the diffractive contribution is suppressed. In this region, the ratio of the $0n0n$ and $0nXn$ cross-sections is measured, providing direct sensitivity to the impact parameter dependence of nPDF modifications, relative to free nucleons.

The measurements presented here were performed using the ATLAS calorimeter, inner detector (ID), trigger, and data acquisition systems [33]. The calorimeter system consists of a liquid argon (LAr) electromagnetic (EM) calorimeter ($|\eta| < 3.2$), a steel/scintillator sampling hadronic calorimeter ($|\eta| < 1.7$), a LAr hadronic calorimeter ($1.5 < |\eta| < 3.2$), and a forward calorimeter (FCal) ($3.2 < |\eta| < 4.9$). The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$ and consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors all immersed in a 2 T axial magnetic field.[1]

Two zero-degree calorimeters [34] (ZDCs) measure neutrons emitted at small rapidity separation from the incident nuclei. For the detector configuration relevant to this measurement, they are tungsten-quartz sampling calorimeters with a total of 4.4 interaction lengths of absorber that are located symmetrically at a distance of ±140 m from the IP and that cover $|\eta| > 8.3$. The luminosity is measured mainly by the LUCID–2 [35] detector.

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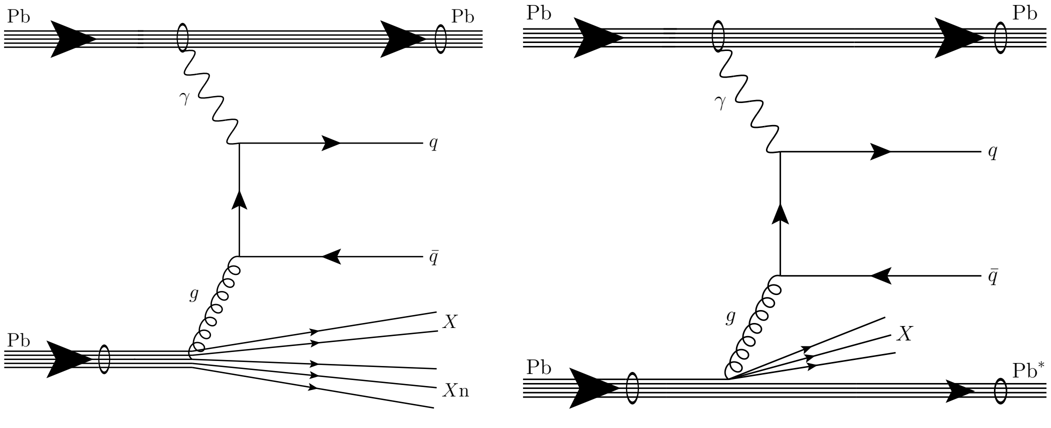
[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z c}{E-p_z c}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.



(a) (b)

Figure 1: Feynman diagrams describing the direct photon case for the two processes measured in this Letter. (a) A $\gamma + A$ interaction where the photon strikes a nucleon near the center of the nucleus, producing a pair of jets while breaking up the nucleus and emitting forward neutrons. (b) A $\gamma + A$ interaction where the photon strikes a nucleon near the edge of the nucleus, producing a pair of jets while leaving the rest of the nucleus intact. In both diagrams, X denotes additional particle production due to color connections between the beam and the jet system on the side of the struck nucleus.

A two-level trigger system is used to select events [36, 37]. The first-level (L1) trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate close to 100 kHz. Both calorimeter and ZDC inputs may be used to accept events in the L1 trigger. Fully assembled events passing the L1 trigger are analyzed and selected for recording using software-based algorithms in the "High-Level" trigger (HLT). A software suite [38] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

These measurements use 1.72 nb^{-1} of Pb+Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV recorded by ATLAS in 2018. The primary triggers used for the measurement involve a combination of $0n0n$ (double veto) ZDC requirements and total transverse energy requirements in the calorimeter at L1, as well as a requirement of at least one jet above a given p_{T} threshold in the HLT. The L1 triggers require a total transverse energy ($\sum E_{\text{T}}$) in the calorimeter which satisfies $5 < \sum E_{\text{T}} < 200$ GeV. The HLT jet triggers are based on the anti-k_t algorithm [39, 40] with radius $R = 0.4$ applied to topological clusters (topo-clusters) [41] formed from energy deposits in the calorimeter. The lowest p_{T} trigger threshold used in this measurement was fully efficient for single jets at 13 GeV (20 GeV) for $|\eta| > 3.2$ ($|\eta| < 3.2$). The efficiency for the HLT trigger to select any of the jets in the final state is greater than 98% for all events within the fiducial acceptance of the measurement. To collect a sample of $0nXn$ jet events, a separate set of triggers were deployed using identical jet and $\sum E_{\text{T}}$ requirements but with an L1 $0nXn$ ZDC trigger.

Monte Carlo (MC) simulated samples were produced using the Pythia 8 event generator [42, 43] with the A14 set of tuned parameters [44] for three relevant physical processes: photonuclear ($\gamma + A \longrightarrow$ jets), photon–pomeron ($\gamma + \mathbb{P} \longrightarrow$ jets), and photon–photon ($\gamma + \gamma \longrightarrow$ jets). The photon flux was computed using Starlight [19], with the integration over impact parameter and the target density performed using methods described in Ref. [18]. For the $\gamma + A \longrightarrow$ jets process, the samples were produced using nCTEQ15 [45] nuclear PDFs. Since Pythia 8 does not simulate forward neutron emission, the same simulated sample is used to model both the $0n0n$ and $0nXn$ $\gamma + A \longrightarrow$ jets events. Hard diffraction with a user-specified pomeron ($\mathbb{P}$) flux was added in Pythia 8 version 8.308 to simulate the process with coherent nuclear pomeron emission. For each of the three samples, the simulated signal events include both direct and resolved photon processes; the latter require additional modeling using the CJKL photon PDF set [46]. Final-state stable particles, defined as those with $c\tau > 10$ mm, were then passed to a Geant4-based simulation of the ATLAS detector [47, 48], the output of which was reconstructed in the same way as data.

Particle-Flow [49] jets are reconstructed using the implementation of the anti-k_t algorithm [39] with radius parameter $R = 0.4$ in the `FastJet` [40] package. These jets use combined calorimeter and tracking information, and a dedicated calibration designed for detector conditions in UPC [18] is applied, derived using methods described in Ref. [50]. Every event must have at least two reconstructed jets with the fiducial requirements: $p_{\text{T}}^{\text{jet}} > 13$ GeV and $|\eta^{\text{jet}}| < 4.4$. From jets satisfying these requirements, the mass (m_{jets}), rapidity (y_{jets}), and total scalar transverse momentum ($H_{\text{T}} \equiv \sum_i p_{\text{T}\,i}^{\text{jet}}$), of the N-jet system resulting from the hard-scattering process are computed. A requirement is also imposed of $0.9 < m_{\text{jets}}/H_{\text{T}} < 4$, consistent with Ref. [18], to reduce the impact of jets not originating from the primary hard-scattering.

Offline requirements are applied to select events recorded during stable running conditions of the LHC, that have no detector hardware or readout error, and that are not consistent with beam-induced backgrounds [18]. UPC $\gamma + A$ events are selected using a combination of offline jet, ZDC, and rapidity gap requirements, in addition to jet selections. Identical event selections (aside from ZDC requirements) are applied to the $0n0n$ and $0nXn$ samples. The $0n0n$ requirement is applied through a veto on events having energy greater than 40% of the beam energy, i.e. more than 1 TeV, in either ZDC. The sum of rapidity gaps on either side of the jets ($\sum \Delta\eta$) is computed using the methodology from Ref. [18], and the maximum sum of rapidity gaps ($\sum_{>} \Delta\eta$) is taken as the larger of the two values. To exclude hadronic Pb+Pb collisions, this quantity is required to satisfy $\sum_{>} \Delta\eta > 2.5$. This requirement removes 22.9% of $0n0n$ events passing all other selections.

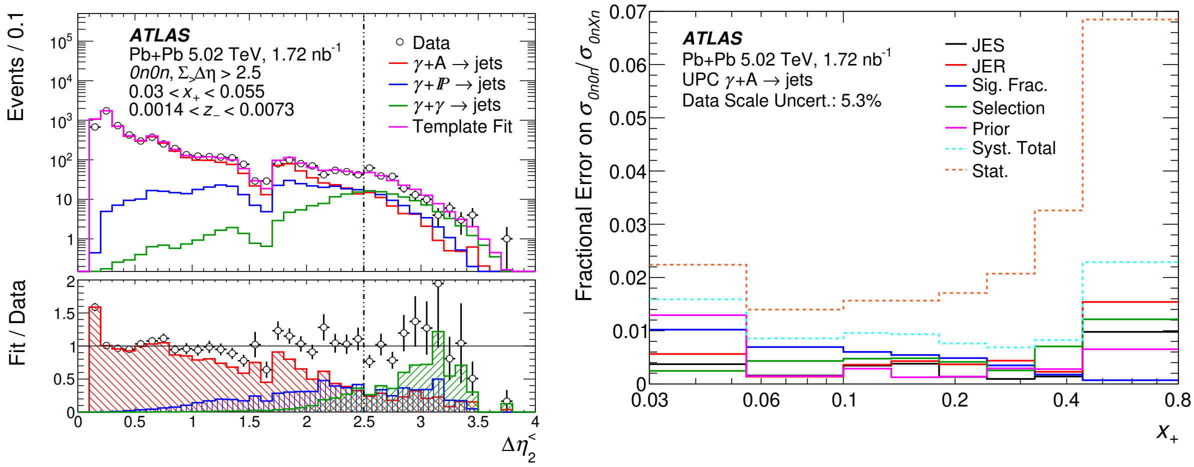
The non-diffractive $\gamma + A$ collisions are intrinsically asymmetric, as the photon energies are usually much smaller than the longitudinal momenta of the struck partons. Thus, the sign of y_{jets} is assumed to indicate the direction of the struck nucleus. Using this assumption, which according to the $\gamma + A \rightarrow$ jets MC sample is valid for more than 99.9% of the studied events, two momentum fractions are defined as:

$$z_{-} \equiv \frac{m_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{-|y_{\text{jets}}|}, \; x_{+} \equiv \frac{m_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{+|y_{\text{jets}}|}. \tag{1}$$

Neglecting initial and final-state radiation and beyond-LO contributions, these correspond to fractions of the beam momentum carried by the partons entering the hard-scattering process from the emitted photon (z_{-}) and struck nucleus (x_{+}).

Event-by-event corrections are applied to the data to account for trigger inefficiencies, which are computed for events that pass all other event selections. Possible trigger inefficiency arises from three sources: the L1 ZDC selections, L1 $\sum E_{\text{T}}$ thresholds, and HLT jet requirements. Studies of the L1 ZDC trigger efficiency indicate that it is greater than 99.9% efficient for selecting $0n0n$ and $0nXn$ events. The efficiency of the L1 $\sum E_{\text{T}}$ and jet requirements are found to rise rapidly at low H_{T}, such that both have at most a 5% inefficiency for $H_{\text{T}} > 28$ GeV, for which a correction is applied. The veto on events with $\sum E_{\text{T}} > 200$ GeV is found to remove no events for the jet kinematics studied, $H_{\text{T}} < 150$ GeV. Both the $\sum E_{\text{T}}$ and jet trigger inefficiencies affect the $0n0n$ and $0nXn$ samples in the same way, so their impact on the ratio is negligible. The efficiency of the $\sum_{>} \Delta\eta > 2.5$ requirement is assessed using Pythia 8 MC samples, where the largest inefficiency in the fiducial region is < 5%. However, since this inefficiency is identical for the $0n0n$ and $0nXn$ samples, it has no impact on the ratio, so no correction is applied. An additional correction to the overall normalization results from independent Pb+Pb EMD scatterings which occur in the same crossing as an event of interest (EMD pile-up). Corrections are derived using the methodology from Refs. [51, 52], and the resulting event-averaged correction to the normalization is 13(7)% for the $0n0n$ ($0nXn$) topology.

While $\sum_{>} \Delta\eta$ characterizes the photon-going direction, a different rapidity gap variable, $\Delta\eta_2$, is more useful to describe the other side of the collision. The $\Delta\eta_2$ variable is defined as the rapidity interval between the edge of the ATLAS detector and the second-closest ID track or topological cluster, on a given side of the detector. The second-closest track or topo-cluster is chosen because two topo-clusters originating from calorimeter noise rarely occur nearby in the same event, while physical deposits are rarely alone, greatly reducing the sensitivity to detector mis-reconstruction effects. The minimum $\Delta\eta_2$ between the two detector sides, $\Delta\eta_2^{<}$, yields distinct distributions for all three processes which contribute to the total $0n0n$ cross-section: $\gamma + A$, $\gamma + \boldsymbol{P}$, and $\gamma + \gamma$. The fraction of the total cross-section associated with $\gamma + A$ processes is assessed via template fits to the $\Delta\eta_2^{<}$ distribution that is explained in greater detail in Ref. [32]. The fits are performed in intervals of (z_{-}, x_{+}) that match the binning of the measured cross-section. An example result from the template-fitting procedure is shown in panel (a) of Figure 2. The measured gap distribution is described as the sum of templates corresponding to the three different processes which contribute to $0n0n$ UPC jet production. The shape at $\Delta\eta_2^{<} = 1.7$ results from the structure of the ATLAS calorimeter which affects the topo-cluster reconstruction. An additional rapidity-gap selection is also applied, requiring $\Delta\eta_2^{<} < 2.5$, in order to reduce sensitivity to uncertainty in the template fitting procedure. In the measured kinematic region, only the lowest two x_{+} intervals have a significant background fraction (5% and 1%, respectively), and the higher-x_{+} intervals have negligible contributions from $\gamma + \boldsymbol{P}$ or $\gamma + \gamma$ processes.



(a)

(b)

Figure 2: (a) An example template fit to the distribution of $\Delta\eta_2^<$, the smallest gap from an edge of the ATLAS detector to the second-closest ID track or topo-cluster, for $0n0n$ UPC jet events in a kinematic interval with substantial contributions from all three components. The $\gamma + A \longrightarrow$ jets template is derived from $0nXn$ data, while the $\gamma + I\!\!P \longrightarrow$ jets and $\gamma + \gamma \longrightarrow$ jets templates are derived from Pythia 8 MC. The lower panel shows the ratio of the different process templates with respect to data, and the markers show the ratio of the full template fit to the data. The dashed line indicates the upper selection on $\Delta\eta_2^<$ applied in order to select a higher-purity $\gamma + A \longrightarrow$ jets sample. (b) The fractional uncertainties on the $0n0n/0nXn$ cross-section ratio from different sources of systematic uncertainty which contribute to this measurement as a function of x_+. The fractional statistical uncertainty is also shown, and it is larger than the combined bin-to-bin systematic uncertainty in all bins. The fully correlated scale uncertainty of ±5.3% is composed of ±0.1% (JES+JER) ±2.5% (Prior) ±0.07% (Sig. Frac.) ±0.6% (EMD pile-up) ±4.7% (EMD).

Once the data are corrected for inefficiencies in the event selections and for residual backgrounds, the fully corrected yields for $\gamma + A \longrightarrow$ jets production as a function of H_T, x_+, and z_- are obtained. These distributions are binned differentially in x_+ using two logarithmic bins between 0.03 and 0.1 and seven logarithmic bins from 0.1 to 0.8, where the two highest-x_+ bins are merged due to limited statistical precision. The binned yields are corrected for residual detector effects with a Bayesian unfolding procedure [53] using the `RooUnfold` package [54] with two iterations. The unfolding response matrices are created from the $\gamma + A \longrightarrow$ jets Pythia 8 MC sample, which is re-weighted so its reconstructed distribution in H_T, x_+, and z_- matches that of the data distribution it is used to unfold ($0n0n$ or $0nXn$). The $0n0n$ and $0nXn$ yields are separately unfolded three-dimensionally in H_T, x_+, and z_-, and the resulting differential cross-sections are integrated over H_T. Statistical uncertainties on the unfolded data distributions are computed using 1000 stochastic variations on the data and response matrices [55]. The effect of the unfolding on the $0n0n/0nXn$ cross-section ratio is typically smaller than the statistical uncertainty.

Systematic uncertainties on the measured cross-section ratios are assessed to account for effects arising from the event selections, jet energy measurement, sensitivity to the unfolding prior, and signal fraction determination. The first three sources partially cancel for the $0n0n/0nXn$ ratio, but the signal fraction uncertainty only impacts the $0n0n$ sample and thus does not exhibit any cancellation. The event selection uncertainties are assessed for the gap requirement ($\sum_> \Delta\eta > 2.5$) by tightening it to $\sum_> \Delta\eta > 3.0$ and re-computing both the cross-sections and gap selection efficiency corrections with this new requirement. The jet response systematic uncertainties are propagated from the uncertainties derived in Ref. [18], following the standard ATLAS jet calibration procedure for Run 2 [50]. The jet response is varied when constructing the response matrices to account for uncertainty in the jet energy scale (JES) and resolution (JER), and the results unfolded with the varied response are compared to results using the nominal jet calibration. An additional p_{T}-dependent uncertainty is assigned on the jet energy scale to account for extrapolating the jet energy measurement from 15 GeV, its nominal limit of applicability, to 13 GeV. The residual sensitivity to the unfolding prior uncertainty is determined by modifying the re-weighting prior distribution in the response matrices. For each variation, the nominal result is compared to a result where both distributions are unfolded with the same prior, either $0n0n$ or $0nXn$.

The numerator of the $0n0n/0nXn$ cross-section ratio is sensitive to the peripheral $\gamma + A$ signal fractions obtained via the template-fitting procedure. The associated systematic uncertainty is evaluated through three variations to the extraction of the signal fraction. The fit range in $\Delta\eta_2^{<}$ is varied, where the first variation removes two additional bins (0.2 units in η) from the start of the fit and the second variation removes the five last bins (0.5 units in η). Uncertainties are also applied to account for imperfect modeling of the topo-cluster reconstruction in simulation. An additional variation is applied where the proportion of direct and resolved photon events in the $\gamma + \gamma$ template is varied to match the fractions observed in Ref. [18]. Additionally, an uncertainty is assessed to account for potential mis-modeling of the shape of the $\gamma + \mathbb{P}$ contribution by performing the fits using modified MC $\gamma + \mathbb{P}$ samples corresponding to conservative variations in the size or shape of the Pb nucleus. These samples were obtained by performing re-weightings of the nominal sample as a function of the momentum-transfer of the pomeron. The varied $\gamma + A \rightarrow$ jets signal fractions are used to re-derive cross-sections, which are then unfolded and compared to the nominal distribution to derive the systematic uncertainties. For more details on this procedure, see Ref. [32]. While this uncertainty is typically quite small in the measured region, the uncertainty in the unfolded results is slightly larger due to possible migration of backgrounds from outside the fiducial region.

A summary of the different contributions to the experimental uncertainty on the $0n0n/0nXn$ cross-section ratio is shown in the right panel of Figure 2. The statistical uncertainty is dominant for all bins, but the largest sources of systematic uncertainty arise from the signal fraction and unfolding prior sensitivity at low x_+. Additionally, fully correlated uncertainties arise due to the luminosity measurement and correction for EMD pile-up. The luminosity uncertainty for the full 2018 Pb+Pb dataset is 2.0%, derived using methods described in Ref. [56], using the LUCID-2 detector for the baseline luminosity measurements [35]. While this uncertainty impacts the absolutely normalized cross-sections, it has no impact on the $0n0n/0nXn$ cross-section ratios. The uncertainty on the absolute cross-section arising due to the correction for EMD pile-up is obtained by varying the Pb+Pb dissociative cross-section within its uncertainties [28]. This variation yields a fractional uncertainty of 0.6% on the absolute cross-sections, with a negligible impact on ratios. An additional uncertainty, which is found to be fully correlated between bins, is applied to account for uncertainty on the correction for additional EMD within the same event, as measured in Refs. [32] and [18] for the $0n0n$ and $0nXn$ cases, respectively.

The fully unfolded ratio of $\gamma + A \rightarrow$ jets cross-sections in $0n0n$ and $0nXn$ topologies as a function of x_+ is shown in Figure 3. For these comparisons, both sets of unfolded cross-sections are corrected for additional EMD within the same event [18, 32]. Since it is possible for differences between the shapes of the $0n0n$ and $0nXn$ cross-sections to arise from modifications to the photon flux probed by each class of events, results are restricted to the range $2 \times 10^{-4} < z_- < 1.4 \times 10^{-3}$. This interval was chosen to select a sample with sufficiently small z_- such that, according to calculations following a procedure from Ref. [11], the results are insensitive to possible modifications in the photon flux in the $0n0n$ sample. This selection removes about 48.4%(51.8%) of the $0n0n$ ($0nXn$) sample. These data show a clearly increasing trend from small to large x_+, indicating a modified slope in the $0n0n$ cross-section relative to the $0nXn$ case. The data are compared with theoretical predictions that assume the $0n0n$ selection corresponds to collisions with unmodified free

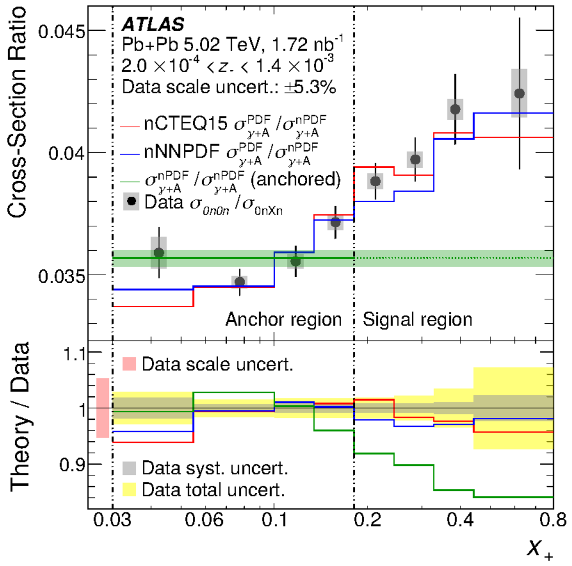


Figure 3: The ratio of $\gamma + A \to$ jets cross-sections for the $0n0n$ neutron topology (numerator) and $0nXn$ neutron topology (denominator) as a function of x_+. Systematic uncertainties are shown as shaded bands, while vertical lines represent combined systematic and statistical uncertainties. The fully correlated component of the systematic uncertainty is subtracted from the bin-to-bin contributions and denoted by the 5.3% scale uncertainty. Theoretical predictions are shown for the ratio of the $\gamma + A \to$ jets cross-section computed in Pythia 8 with unmodified PDFs divided by the result with modified nPDFs, for nCTEQ [57] (red) and nNNPDF [58] (blue). The green line represents the null hypothesis that the $0n0n$ and $0nXn$ samples exhibit the same nPDF modification. Each prediction is scaled to match the integral in the anchor region, and the uncertainty on this normalization is shown as the shaded green band. The bottom panel shows the ratio of the different predictions to the data, with statistical and total uncertainties shown as shaded yellow and gray bands, respectively.

nucleons. The predicted cross-sections with nPDF modifications ($\sigma^{\mathrm{nPDF}}_{\gamma+A}$) for these comparisons are derived from nCTEQ15 WZ+SIH [57] (red) and nNNPDF 3.0 [58] (blue). The corresponding cross-sections computed with baseline free nucleon PDFs ($\sigma^{\mathrm{PDF}}_{\gamma+A}$) are derived from CT18 [59] and NNPDF 3.1 [60], respectively. All samples account for the isospin of lead. As the theoretical predictions provide no absolute normalization for the ratio, they are scaled to match the ratio of the cross-section integrals in the region ($0.03 < x_+ < 0.1811$), the choice of which is motivated below. The agreement in shape between the theoretical comparisons and the data is consistent with photonuclear interactions at the nuclear periphery behaving as if the nucleons are free and unmodified by nuclear effects.

To evaluate the statistical significance of the observed modification to the x_+ distribution, a test is performed that takes advantage of the fact that the impact of the nuclear modifications on the measured ratio is monotonic in x_+. Namely, the measured x_+ range is divided into "anchor" and "signal" regions within which the $0n0n$ and $0nXn$ cross-sections are separately summed. The $0n0n$/$0nXn$ cross-section ratios are then computed in each region, and the "null" hypothesis that the ratios are the same in the two regions is tested. The division between signal and anchor regions was determined prior to examining the data, using purely MC samples. Specifically, hypothetical $0n0n$ cross-sections were computed using Pythia 8 $\gamma + A \to$ jets samples with different combinations of modified and unmodified nPDFs, which were re-sampled to match the number of events in the data. Ratios to simulated $0nXn$ cross-sections were computed in both the anchor and signal regions using different boundaries in the measured x_+ range. Taking into account statistical and systematic uncertainties on the data, these studies indicated an optimal division with anchor and signal regions of ($0.03 < x_+ < 0.1811$) and ($0.1811 < x_+ < 0.8$), respectively. An expected significance of 6.5 σ is obtained in MC studies where the $0n0n$ cross-section is computed from free nucleon – *i.e. unmodified* – PDFs and the $0nXn$ using nCTEQ [57] nPDFs. Then, computing the significance in data using this division between anchor and signal regions, the measured cross-section ratios exclude the null hypothesis with an observed significance of 6.0σ, which is mostly insensitive to variations in the boundary between the anchor and signal regions. This result indicates an observation of a significant difference in the nuclear PDFs probed by the $0n0n$ and $0nXn$ selections within the signal x_+ range and, thus, of a significant b_A-dependence in the nPDF.

In summary, ATLAS has studied jet photoproduction in ultra-peripheral 5.02 TeV Pb+Pb collisions in which both nuclei remain intact, comparing them to collisions where one nucleus dissociates . The lack of nuclear breakup is determined by the absence of beam-rapidity neutrons in ZDCs. At small z_- (larger $|y_\mathrm{jets}|$), the non-diffractive $\gamma + A$ cross-section dominates, and a measurement of jet photoproduction in hard $\gamma + A$ scattering with no nuclear breakup is possible. The ratio of jet cross-sections between the $0n0n$ and $0nXn$ collision events is measured, and it shows a clear dependence on x_+. This feature indicates a different, x_+-dependent, modification of the nPDFs in the $0n0n$ and $0nXn$ topologies. Since the $0n0n$ selection is expected to preferentially select peripheral (large b_A) collisions while the $0nXn$ requirements selects all other $\gamma + A$ collisions, the observed difference is consistent with a lack of nuclear modifications in peripheral events. Such a conclusion could have consequences for interpreting results from the heavy ion programs at RHIC, the LHC, and the HL-LHC. It also demonstrates a method for studying the b_A-dependence of nPDF modifications at both the HL-LHC and the future electron-ion collider. The observed significance in rejecting the null hypothesis that the $0n0n$ collisions probe the same nuclear PDFs as $0nXn$ collisions is 6.0σ, providing the first evidence that the parton distributions of nucleons near the edge of a nucleus differ from those of nucleons near its center.

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End matter

Figure 4 demonstrates the geometry of a photonuclear collision, where the two colliding nuclei are separated by the two-nucleus impact parameter ($\vec{b}_{\rm AA}$) which satisfies $|\vec{b}_{\rm AA}| > 2R_{\rm A}$. The impact parameters of the collision with respect to the two nuclei are $\vec{b}_\gamma$ and $\vec{b}_{\rm A}$ for the photon-emitting and struck nuclei, respectively. These impact parameters satisfy $\vec{b}_{\rm AA} = \vec{b}_{\rm A} - \vec{b}_\gamma$.

The cross-sections for $\gamma + A \rightarrow$ jets production in $0n0n$ and $0nXn$ neutron topologies are shown in Figure 5. These results provide the numerator and denominator, respectively, for the ratio shown in Figure 3. The cross-sections are corrected for the impact of additional EM dissociation, as measured in Ref. [32]. In each case, the data scale uncertainties and point-to-point systematic uncertainties are dominated by uncertainty on the jet energy scale and resolution. The similar shapes of the cross-sections, with the $0n0n$ cross-section about 0.04 times the $0nXn$, is consistent with the $0n0n$ measuring a small fraction of the total non-diffractive $\gamma + A$ cross-section where no forward neutrons are emitted by either nucleus.

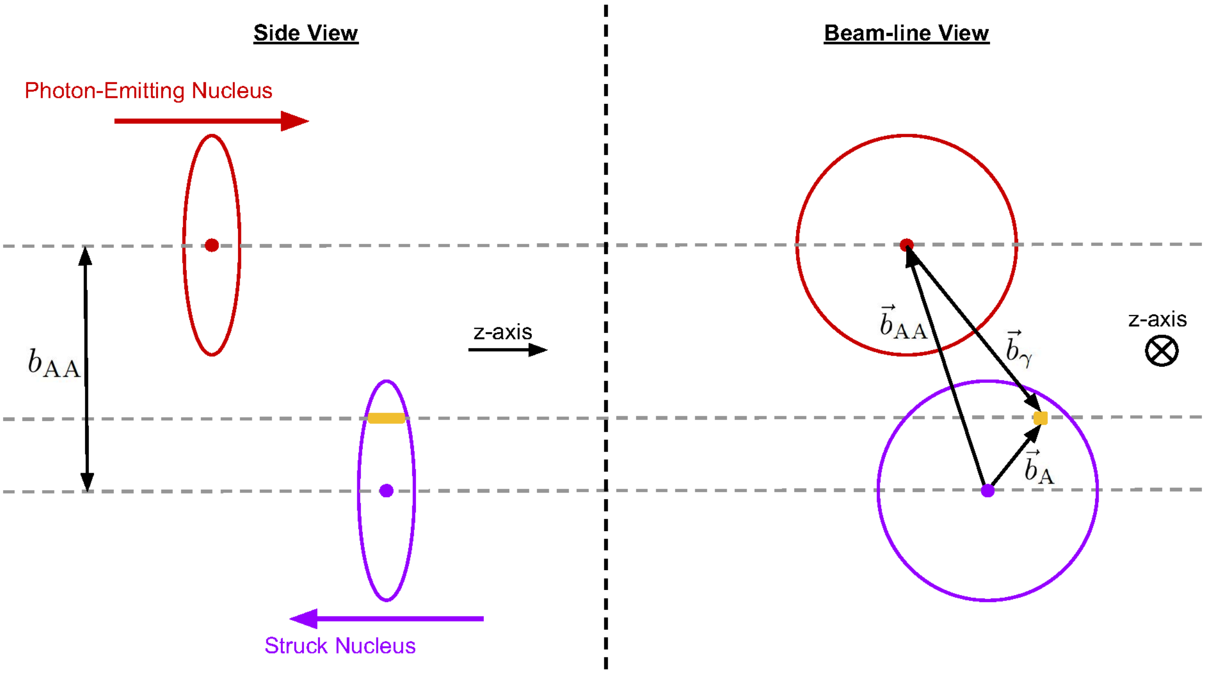

Figure 4: A diagram of an ultra-peripheral photonuclear collision between two heavy ions, shown from a side view (left) or beam-line view (right). The photon-emitting nucleus (red) and struck nucleus (purple) are separated by impact parameter $\vec{b}_{\rm AA}$. The two vectors $\vec{b}_\gamma$ and $\vec{b}_{\rm A}$ indicate the distance from the site of the $\gamma + A$ interaction (orange) to the centers of the photon-emitting and struck nuclei, respectively.

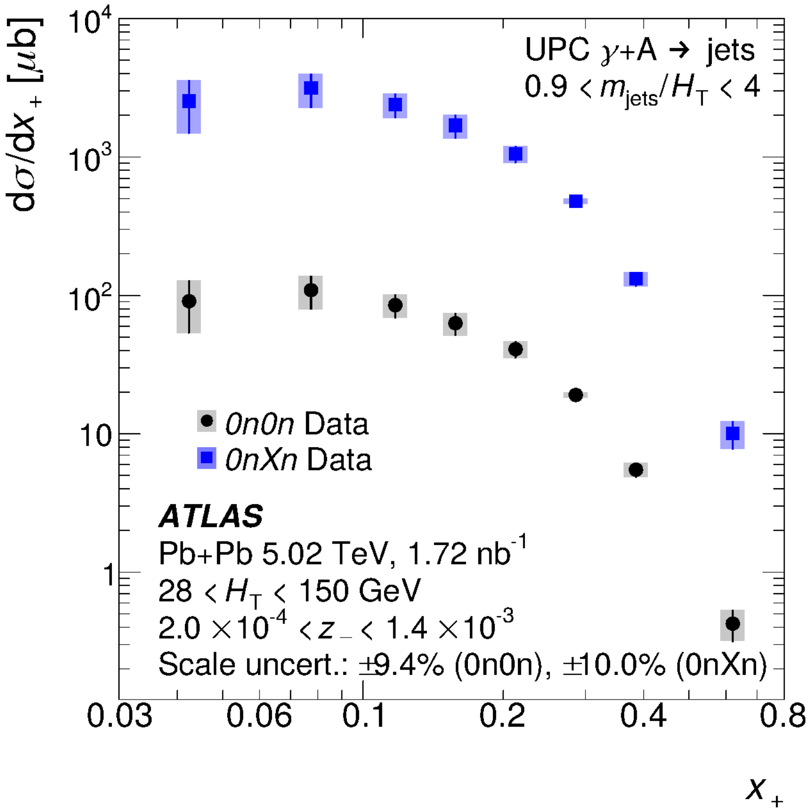

Figure 5: Cross-sections for photonuclear jet production measured with $0n0n$ (black) and $0nXn$ (blue) neutron topologies. Systematic uncertainties are shown as shaded bands, and the combined statistical and systematic uncertainties are shown as vertical lines. The fully correlated component of the systematic uncertainty is subtracted from the bin-to-bin contributions and denoted by the $0n0n$ and $0nXn$ scale uncertainties. The kinematic selections applied here are identical to those used in Figure 3.

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