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https://doi.org/10.1103/7lx4-x8rw

Charged-hadron and identified-hadron (K^0_S, Λ, Ξ^-) yield measurements in photonuclear Pb + Pb and p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ATLAS

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(Received 12 March 2025; accepted 5 May 2025; published 17 June 2025)

This paper presents the measurement of charged-hadron and identified-hadron (K^0_S, Λ, Ξ^-) yields in photonuclear collisions using 1.7 nb^{-1} of $\sqrt{s_{NN}} = 5.02$ TeV Pb + Pb data collected in 2018 with the ATLAS detector at the Large Hadron Collider. Candidate photonuclear events are selected using a combination of tracking and calorimeter information, including the zero-degree calorimeter. The yields as a function of transverse momentum and rapidity are measured in these photonuclear collisions as a function of charged-particle multiplicity. These photonuclear results are compared with 0.1 nb^{-1} of $\sqrt{s_{NN}} = 5.02$ TeV p + Pb data collected in 2016 by ATLAS using similar charged-particle multiplicity selections. These photonuclear measurements shed light on potential quark-gluon plasma formation in photonuclear collisions via observables sensitive to radial flow, enhanced baryon-to-meson ratios, and strangeness enhancement. The results are also compared with the Monte Carlo DPMJET-III generator and hydrodynamic calculations to test whether such photonuclear collisions may produce small droplets of quark-gluon plasma that flow collectively.

DOI: 10.1103/7lx4-x8rw

I. INTRODUCTION

When ultrarelativistic beams of lead nuclei are brought into collision, the processes often studied are those for which the nuclei have an impact parameter smaller than twice the nuclear radius. Such collisions are now understood to create droplets of quark-gluon plasma (QGP) that flow as a nearly perfect fluid, i.e., hydrodynamically [1]. However, the strong electromagnetic (EM) fields of the fully ionized nuclei can also induce interactions when the nuclei have significantly larger impact parameters [2,3]. In the equivalent photon approximation, these strong EM fields correspond to a flux of quasi-real, high-energy photons. Importantly, the nuclei can produce high-energy photons coherently from the entire nucleus, resulting in an enhancement to the photon spectrum over a broad energy range which is proportional to Z^2 (e.g., atomic number $Z = 82$ for Pb).

As a result, the rates for EM interactions (which include photon–photon and photon–nucleus scatterings) are large enough to be measurable in Pb+Pb collisions at the Large Hadron Collider (LHC). Such collisions are commonly referred to as "ultraperipheral collisions" (UPCs) because they can occur when the impact parameters between the incoming nuclei are large enough such that there is no hadronic interaction between the nuclei. The ATLAS Collaboration has measured UPC events where the basic interactions are photon–photon collisions [4–7], including light-by-light scattering and scattering where two leptons in the final state are produced. The ATLAS Collaboration has also measured UPC photonuclear collisions, for example, in the case of dijet production [8]. In photonuclear reactions, the photon could act as a pointlike particle interacting with a parton in the nucleus (the "direct" case). However, the vector-meson dominance picture suggests that the photon could fluctuate to a vector meson, for example, a ρ meson, which then interacts with the Pb nucleus (the "resolved" case) [2,9]. Therefore, some subset of these collisions could be considered as ρ–nucleus collisions, albeit at a lower center-of-mass collision energy than the nucleon-nucleon $\sqrt{s_{NN}}$, depending on the ρ energy. Hence, such events will have an overall rapidity boost of the center-of-mass frame in the direction of the nucleus.

Two-particle azimuthal correlations have been measured in photonuclear (γ + Pb) events by ATLAS [10]. These results indicate significant nonzero elliptic (v_2) and triangular (v_3) flow coefficients. These coefficients have been interpreted in terms of a hydrodynamically flowing medium [11], and alternatively in terms of scattering diagrams in the glasma framework [12]. The v_2 values are significantly smaller in photonuclear events compared with p + Pb events at the same charged particle multiplicity $N^{\rm rec}_{\rm ch}$. The lower elliptic flow in photonuclear events may be explained by the stronger longitudinal decorrelations in the rapidity-shifted photonuclear events in hydrodynamic calculations [11]. These authors make the specific prediction that the radial flow [13] is essentially the same in photonuclear and p + Pb collisions, as measured via the mean transverse momentum, $p_{\rm T}$, of charged and identified particles. The formation of a small QGP droplet may also lead to other manifestations of QGP seen in heavy-ion collisions such as a baryon/meson enhancement [14] and strangeness enhancement [15,16]. A measurement by CMS

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of two-particle correlations in the lower-multiplicity $\gamma + p$ system did not find evidence for collective effects when compared to the expectation from event generators [17].

This paper presents the yields of charged hadrons and identified strange hadrons (K^0_S, Λ, Ξ^-) in photonuclear collisions using 1.7 nb^{-1} of $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb data collected in 2018 with the ATLAS detector at the LHC. The results are compared with measurements in $p+\text{Pb}$ collisions specifically to test the predictions of Ref. [11]. Additionally, these photonuclear data are compared with the photonuclear Monte Carlo (MC) DPMJET-III [18,19] generator and with hydrodynamic calculations [11] to test the hypothesis of a small QGP droplet formation.

II. ATLAS DETECTOR

The ATLAS detector [20] at the LHC [21] covers nearly the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting magnets. The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$.

The high-granularity silicon pixel detector covers the vertex region and typically provides three measurements per track. An innermost insertable B-layer [22] has been operating as a part of the pixel detector since 2015. It is followed by the silicon microstrip tracker (SCT) which usually provides four two-dimensional measurement points per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) electromagnetic calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$, to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillating-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters covering $1.5 < |\eta| < 3.2$. The angular coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic measurements, respectively. The muon spectrometer (MS) surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The MS includes a system of precision tracking chambers and fast detectors for triggering. The minimum-bias trigger scintillator, reconfigured for Run 2, detects charged particles over $2.07 < |\eta| < 3.86$ using two hodoscopes of 12 counters positioned at $z = \pm 3.6$ m. The zero-degree calorimeters (ZDCs) play a key role in identifying UPC events in heavy-ion collisions. They are located at $z = \pm 140$ m from the interaction point, just beyond the point where the common straight-section vacuum-pipe divides back into two independent beam-pipes. The ZDC modules consist of layers of alternating quartz rods and tungsten plates that measure neutral particles at pseudorapidities $|\eta| > 8.3$.

A two-level trigger system [23] is used to select events. The first-level trigger (L1) is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to at most 100 kHz. This is followed by the software-based high-level trigger (HLT) that reduced the accepted event rate to 1–4 kHz depending on the data-taking conditions during 2018 Pb+Pb collisions.

A software suite [24] 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.

III. EVENT SELECTION AND SIMULATIONS

Photonuclear interactions are selected via event topologies where one of the Pb nuclei remains intact, resulting in no spectator neutrons and very sparse particle production downstream of the given nucleus. This is taken to be the photon-going direction. The datasets and event selection for photonuclear collisions are identical to those used in a previous measurement of two-particle azimuthal correlations [10], and are briefly summarized below.

The measurements presented in this paper were performed using the $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb dataset collected with a variety of triggers in 2018, with a total integrated luminosity of 1.7 nb^{-1}. The 25-track high-multiplicity trigger (HMT), 15-track HMT, and the minimum-bias (MB) trigger were configured with progressively higher prescale factors, sampling 1.6 nb^{-1}, 0.13 nb^{-1}, and 1.0 μb^{-1} of data, respectively. Photonuclear candidate events were first selected by the trigger requiring one ZDC side (referred to as the Pb-going side and corresponding to $\eta < 0$) to have a minimum amount of energy at L1, $E > 1$ TeV, consistent with the presence of one or more neutrons. The other side (referred to as the photon-going side and corresponding to $\eta > 0$) was required to have energy below a maximum-energy cutoff, $E < 1$ TeV, consistent with no neutrons. The per-nucleon energy is 2.5 TeV, leading to a single neutron peak energy well above this 1 TeV threshold [4]. The selected topology is referred to as "0nXn." Events were also required to satisfy an upper bound of 200 GeV on the total transverse energy deposited across all central calorimeters at L1, for further rejection of hadronic Pb + Pb events.

Reconstructed pseudorapidity gap quantities, constructed using charged-particle tracks and clusters of energetic calorimeter cells in each event, are used to distinguish between different physics processes such as photonuclear col-

[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. Cylindrical 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 $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\Phi)^2}$. Both the rapidity and pseudorapidity are calculated in the center-of-mass frame per nucleon pair.

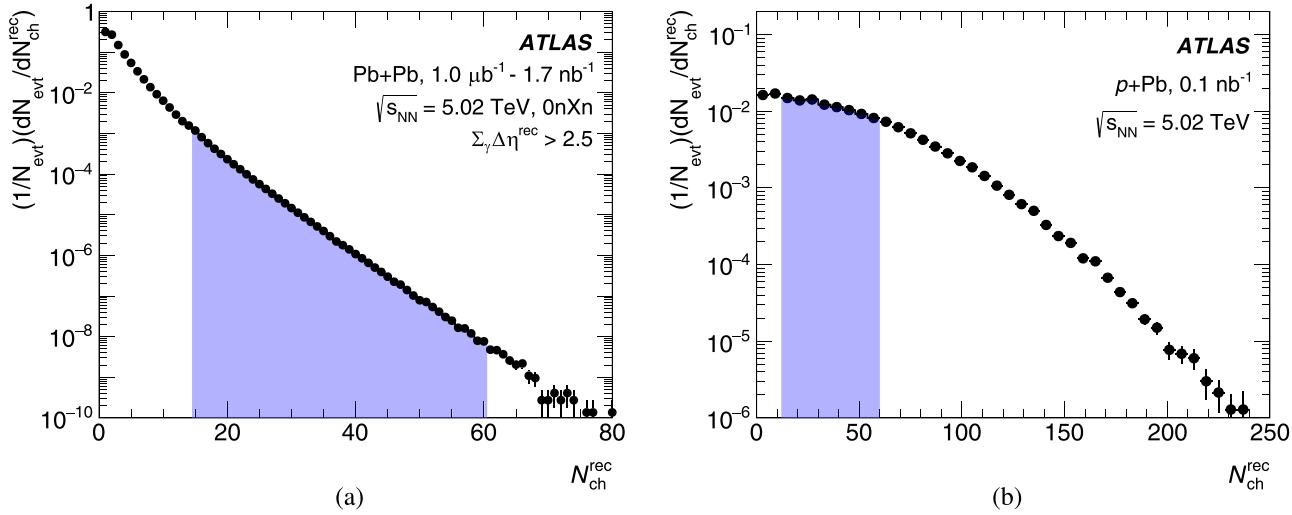


FIG. 1. Multiplicity distributions (N_{ch}^{rec}) from (a) Pb+Pb photonuclear and (b) $p+$Pb collisions. The N_{ch}^{rec} range utilized in this paper, $15 \leqslant N_{ch}^{rec} \leqslant 60$, is highlighted.

lisions, low-activity (peripheral) hadronic Pb + Pb collisions, and $\gamma\gamma \to X$ processes. The requirement of a rapidity gap above a minimum value in the photon-going direction can efficiently remove peripheral Pb + Pb events. Rather than the traditional pseudorapidity gap quantity [25], which determines the pseudorapidity difference between the edge of the detector and the closest particle, an alternative "sum-of-gaps" definition is used, which adds together contiguous gaps separated by particle production concentrated in a narrow pseudorapidity region. This alternative definition is used to retain a large selection efficiency for resolved photon events where a large contiguous pseudorapidity gap may otherwise be spoiled by a hadronic fragment on the photon-going side. The quantity $\sum_\gamma \Delta\eta^{rec}$ corresponds to the sum-of-gaps calculated in the photon-going half of the detector, and is constructed using tracks with $p_T > 0.4$ GeV, $|\eta| < 2.5$ and clusters with $p_T > 0.2$ GeV, $|\eta| < 4.9$ in each event. It is calculated by first sorting the tracks and clusters in η. The differences in η between adjacent particles, $\Delta\eta$, are included in the sum if they are larger than 0.5. The value of 0.5 was observed in the simulation to retain good efficiency for resolved photon events. The gap calculation is computed as always starting from mid rapidity to the edge of the detector; thus, $\sum_\gamma \Delta\eta^{rec}$ ranges from 0 to 4.9. UPC events with $\sum_\gamma \Delta\eta^{rec} > 2.5$ are utilized in this paper following the procedure in Ref. [10].

Despite the 0nXn ZDC and $\sum_\gamma \Delta\eta^{rec}$ selections, a residual contamination of the photonuclear events by Pb+Pb peripheral inelastic collisions remains, which is smaller than 3%. To account for this, a small purity correction factor and associated systematic uncertainties are applied, as performed in Ref. [10]. No other backgrounds, such as from $\gamma\gamma$ processes, were found to be significant after the event selection.

This paper includes comparisons with the 2016 $p+$Pb collision data collected at $\sqrt{s_{NN}} = 5.02$ TeV, with an integrated luminosity of 0.1 nb^{-1}, obtained using a minimum-bias trigger as detailed in Ref. [26]. In the $p+$Pb system, positive and negative (pseudo)rapidities denote the proton- and nucleus-going directions, respectively.

Each event is characterized by the number of reconstructed tracks with $p_T > 0.4$ GeV and $|\eta| < 2.5$, referred to as the reconstructed charged-particle multiplicity (N_{ch}^{rec}). This standard ATLAS heavy-ion event class definition utilizes reconstructed tracks that are not corrected for track acceptance and efficiency; see, for example, Refs. [27–30]. Monte Carlo studies indicate that selections on N_{ch}^{rec} correspond to equivalent selections on truth-level charged particles with $p_T > 0.4$ GeV and $|\eta| < 2.5$ as well, but with an average value of $N_{ch}^{truth} \approx 1.2 \times N_{ch}^{rec}$. Figure 1 shows the N_{ch}^{rec} distributions in photonuclear Pb+Pb and $p+$Pb events. The N_{ch}^{rec} range utilized in this paper, $15 \leqslant N_{ch}^{rec} \leqslant 60$, is highlighted. The N_{ch}^{rec} differential results are presented in the range $15 \leqslant N_{ch}^{rec} \leqslant 60$ and N_{ch}^{rec} integrated results are shown for $25 \leqslant N_{ch}^{rec} \leqslant 60$. The $p+$Pb events are then reweighted to have effectively the same N_{ch}^{rec} distribution as the UPC Pb+Pb events.

The simulated event sample for the photonuclear analysis is generated with DPMJET-III + STARLIGHT. Events were generated with different minimum requirements on N_{ch}^{rec} to provide a good statistical coverage over the N_{ch}^{rec} range accessed in data. First, the distribution of photon flux for Pb beams at the LHC was calculated using STARLIGHT [31]. The flux distribution was passed to a multipurpose generator based on the Dual Parton Model (DPM) and referred to as DPMJET-III [18,19], which simulates direct and resolved photon–lead ($\gamma+$Pb) interactions at the generator level.

The DPM model is a diagrammatic way of describing particle production in hadron–hadron collisions [32]. There are two major concepts that underlie the dual-parton model. The first is the dual resonance model [33], which assumes that there are two alternative (or "dual") descriptions of hadron–hadron interactions—the t-channel diagram where particles can be exchanged as a form of interaction and the s-channel diagram where the two incoming particles fluctuate into an intermediate state and then interact. The second is the Veneziano

scattering amplitude, which allows for a convergent calculation of the scattering amplitude for the exchange of a large set of particles. These two concepts enable calculations in soft hadron physics through *pomeron* exchange. The pomeron is a particle with vacuum quantum numbers analogous to a closed string and can be exchanged between hadrons as a form of interaction. Thus, through the dual resonance model there are intermediate states in elastic hadron–hadron collisions with a large number of pomerons. These diagrams can be "cut" to calculate the amplitude of the inelastic process of hadrons interacting to form a large number of primarily meson final states. The DPMJET-III MC generator combines the DPM with perturbative QCD (pQCD), as well as other features, to attempt a full description of hadron–hadron, hadron–photon, and photon–photon collisions [19]. The full set of particles was then run through a full GEANT4 [34] simulation of the ATLAS detector. A sample of thirteen million γ + Pb events were generated.

The simulated event sample for the p + Pb analysis is generated with HIJING [35]. The HIJING model combines pQCD inspired models for multiple-jet production with low-p_{T} multistring phenomenology. The model thus extends the PYTHIA string picture [36] to include modeling of both high-energy pp collisions, as well at p–nucleus and nucleus–nucleus collisions. The geometry for multiple collisions in p–nucleus and nucleus–nucleus collisions is provided by MC Glauber [37]. The model also includes multiple mini-jet production, nuclear shadowing of parton distribution functions, and a schematic mechanism of jet interactions in dense matter. The phenomenological parameters are adjusted to reproduce essential features of pp multiparticle production data for a wide energy range ($\sqrt{s_{NN}} = 5$ GeV to 2 TeV). For the sample used here the so-called "jet quenching" feature is turned off. A sample of five million p + Pb HIJING events was generated.

IV. ANALYSIS

This paper reports charged-hadron and identified-strange-hadron yields reconstructed using tracks in the inner tracker with $p_{\mathrm{T}} > 0.1$ GeV and $|\eta| < 2.5$. Both utilize the same event selection criteria detailed above. Additionally, the yields are determined in both photonuclear Pb+Pb and p + Pb using identical track reconstruction and extraction methods.

A. Charged hadrons

The charged-hadron analysis utilizes tracks that originate from the collision, referred to as primaries. Primary particles are defined as charged particles with a lifetime $\tau > 3 \times 10^{-10}$ s, either directly produced in the collision or from subsequent decays of directly produced particles with $\tau < 3.0 \times 10^{-11}$ s. This definition excludes charged strange baryons that have a very small probability to actually traverse the tracker before decaying (for example, the Ξ^- with $\tau = 1.6 \times 10^{-10}$ s and Ω^- with $\tau = 0.8 \times 10^{-10}$ s). However, it includes charged hadrons from the decay of Δ resonances and ρ mesons with lifetimes shorter than 3.0×10^{-8} s. The contribution of charged leptons is negligible and thus the tracks represent charged hadrons. The track reconstruction follows that utilized for low pileup pp data-taking [38,39]. The reconstructed tracks are required to satisfy quality criteria as detailed in Ref. [40]. Tracks are further required to have $p_{\mathrm{T}} > 0.1$ GeV, $|\eta| < 2.5$, and a distance of closest approach to the reconstructed vertex in both the longitudinal and transverse directions of less than 1.5 mm.

The reconstructed tracks are then used to calculate charged-hadron yields as functions of p_{T} in different η slices:

$$Y_1(\eta, p_{\mathrm{T}}) = \frac{1}{N_{\mathrm{ev}}} \frac{\mathrm{d}N_{\mathrm{ch}}^2}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \tag{1}$$

and then yields integrated over p_{T} as a function of η:

$$Y_2(\eta) = \frac{1}{N_{\mathrm{ev}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}, \tag{2}$$

where N_{ev} is the number of selected events and N_{ch} is the number of charged particles.

The tracks entering these observables in bins of p_{T} and η are corrected for reconstruction and selection inefficiency, as well as for contributions from tracks that are not associated with primary particles, on a per-track basis using simulation-derived correction factors.

The reconstruction efficiency is defined as the ratio of the number of truth primary charged particles whose associated reconstructed track has a truth-matched primary charged particle $N_{\mathrm{truth}}^{\mathrm{matched}}$ (as defined in Ref. [41]) to the total number of truth primary charged particles, N_{truth}, as a function of both p_{T} and η:

$$\varepsilon(\eta, p_{\mathrm{T}}) = \frac{N_{\mathrm{truth}}^{\mathrm{matched}}(\eta, p_{\mathrm{T}})}{N_{\mathrm{truth}}(\eta, p_{\mathrm{T}})}. \tag{3}$$

The contributions to reconstructed tracks that are not associated with primary particles are classified into fake tracks and secondary tracks. To correct for these contributions, tracks are weighted on a track-by-track basis by the "primary fraction," f_{primary}, which is estimated as a function of reconstructed kinematics in simulated events by taking the ratio of the number of primary tracks $N_{\mathrm{ch}}^{\mathrm{primary}}$ to the number of reconstructed tracks N_{ch}:

$$f_{\mathrm{primary}}(\eta, p_{\mathrm{T}}) = \frac{N_{\mathrm{ch}}^{\mathrm{primary}}(\eta, p_{\mathrm{T}})}{N_{\mathrm{ch}}(\eta, p_{\mathrm{T}})}. \tag{4}$$

The yields as a function of η are measured for $p_{\mathrm{T}} > 0.1$ GeV and extrapolated using the DPMJET-III MC down to $p_{\mathrm{T}} = 0$ GeV, i.e., correcting the yields by the fraction of DPMJET-III charged particles with $p_{\mathrm{T}} > 0.1$ GeV to charged particles down to $p_{\mathrm{T}} = 0$ GeV. These correction factors are 5–15% in photonuclear Pb+Pb and 5–7% in p + Pb collisions.

Finally, using the yields detailed above, the $\langle p_{\mathrm{T}} \rangle$ in η intervals are calculated as a function of $N_{\mathrm{ch}}^{\mathrm{rec}}$. When calculating $\langle p_{\mathrm{T}} \rangle$ the extrapolation down to $p_{\mathrm{T}} = 0$ GeV is performed using a Modified Hagedorn fit [42]:

$$\frac{1}{N}\frac{dN}{dp_{\mathrm{T}}} = A_1 \frac{p_{\mathrm{T}}^2}{\sqrt{p_{\mathrm{T}}^2 + m_0^2}} \left(1 + \frac{p_{\mathrm{T}}}{p_1}\right)^{-n_1}, \tag{5}$$

where m_0 is the rest mass of considered particle, p_1 and n_1 are the free parameters, and A_1 is the normalization constant. The

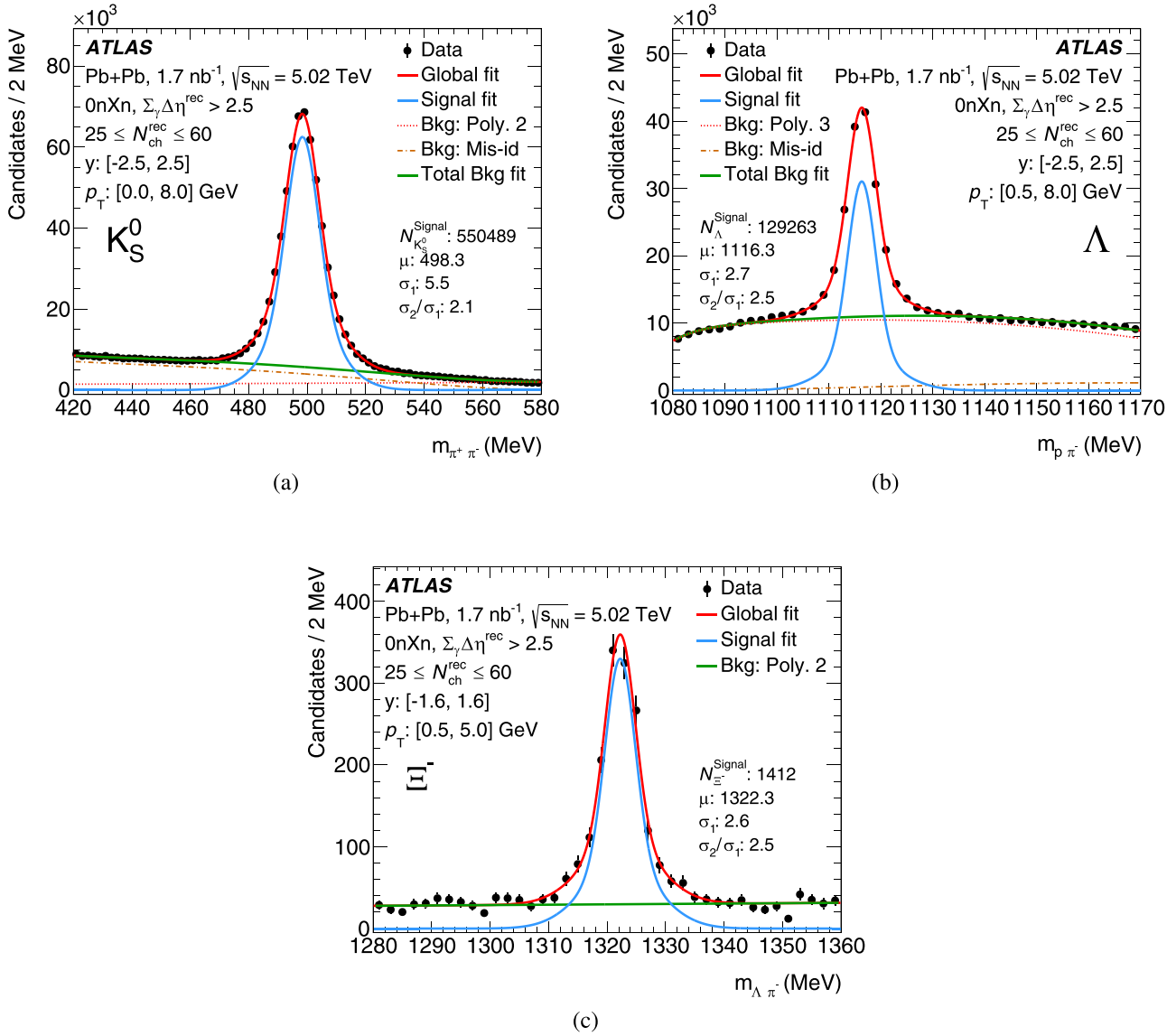


FIG. 2. Invariant-mass distributions of (a) K^0_S, (b) Λ, and (c) Ξ^- in Pb+Pb photonuclear collisions. The data are fitted to a signal (double Gaussian) and a background component (detailed in the text). The signal counts, and fit parameters for the mean μ and widths σ_1 and σ_2 of the double Gaussian are also shown in units of MeV.

$\langle p_T \rangle$ in each η bin and in each N_{ch}^{rec} bin is calculated by finding the mean value of the fit results for $p_T > 0$ GeV.

B. Identified strange hadrons

Only the K^0_S, Λ, and Ξ^- originating from the primary vertex are considered. The contribution of secondary Λ from Σ^0 decay is included, while contributions from the decay products of heavy baryons (Ξ^-, Ω^-) are excluded from the definition of primary Λ. For Λ and Ξ^-, the definition includes only the baryon state and does not represent an average of baryons and antibaryons. Antibaryons have an additional acceptance correction due to annihilation processes, and GEANT4 is known to not model this correctly [43,44].

Identified strange hadrons are reconstructed using oppositely charged tracks with $p_T > 0.1$ GeV and $|\eta| < 2.5$, which are fitted to a common secondary vertex using a Kalman filter [45]. The K^0_S candidates in the $\pi^+ + \pi^-$ decay mode (branching ratio of 69.2%) are required to satisfy the following criteria:

(i) The χ^2 of the two-track vertex fit is required to be less than 15 (with one degree of freedom).

(ii) The cosine of the pointing angle in the transverse plane ($\cos\theta$) between the K^0_S momentum vector and the K^0_S flight direction, defined as the line connecting the reconstructed primary vertex to the decay direction, is required to fulfill the requirements:
   (a) $\cos\theta > 0.999$ for Pb+Pb photonuclear collisions, except in the most backward rapidity bin, y: $[-2.5, -1.6]$, $\cos\theta > 0.9999$.
   (b) $\cos\theta > 0.995$ for p + Pb, except in the most backward and forward rapidity bins of p + Pb, y: $[-2.5, -1.6]$ and y: $[1.6, 2.5]$, $\cos\theta > 0.999$

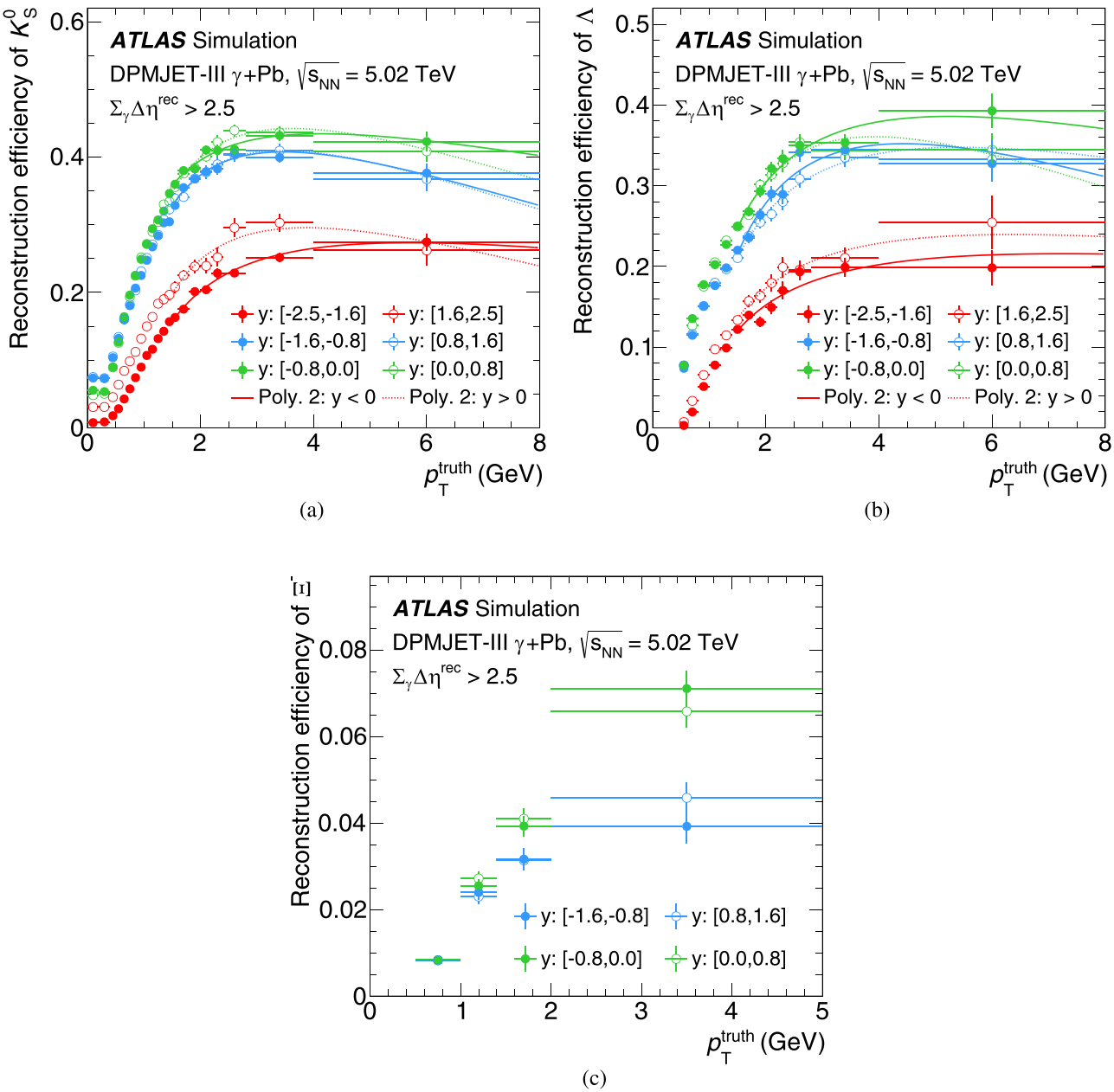


FIG. 3. Reconstruction efficiencies of (a) K^0_S, (b) Λ, and (c) Ξ^- as a function of p_T^{truth} in intervals of y^{truth} as determined using DPMJET-III. The efficiencies are fitted using polynomial functions for K^0_S and Λ. Statistical uncertainties are shown as vertical lines.

(c) Requirements on the minimum values of the variables $|\frac{L_{xy}}{\sigma_{L_{xy}}}|$ and $|\frac{p_T}{\sigma_{p_T}}|$, in bins of p_T and y. These are optimized using the Toolkit for Multivariate Data Analysis (TMVA) package within the ROOT framework [46], where L_{xy} is the distance from the reconstructed primary vertex to the reconstructed secondary vertex (decay vertex of the K^0_S candidate) in the transverse plane, $\sigma_{L_{xy}}$ is the uncertainty on L_{xy} reconstruction, p_T is the reconstructed momentum of the K^0_S candidate and σ_{p_T} is the uncertainty in the p_T reconstruction.

The Λ candidates in the $p + \pi^-$ decay mode (branching ratio of 63.9%) are required to satisfy the following criteria:

(i) The p_T of the Λ candidate is greater than 0.5 GeV.
(ii) The χ^2 of the two-track vertex fit is required to be less than 15 (with one degree of freedom).
(iii) The cosine of the pointing angle ($\cos\theta$) is required to be greater than 0.999.
(iv) Requirements on the minimum values of the variables $|\frac{L_{xy}}{\sigma_{L_{xy}}}|$ and $|\frac{p_T}{\sigma_{p_T}}|$, in bins of p_T and y, determined using the TMVA package as above.

The Ξ^- candidates in the $\Lambda + \pi^-$ decay mode (branching ratio of 99.5%) are required to satisfy the following criteria:

(i) The p_T of the Ξ^- candidate is greater than 1 GeV, and $|y| < 1.6$.

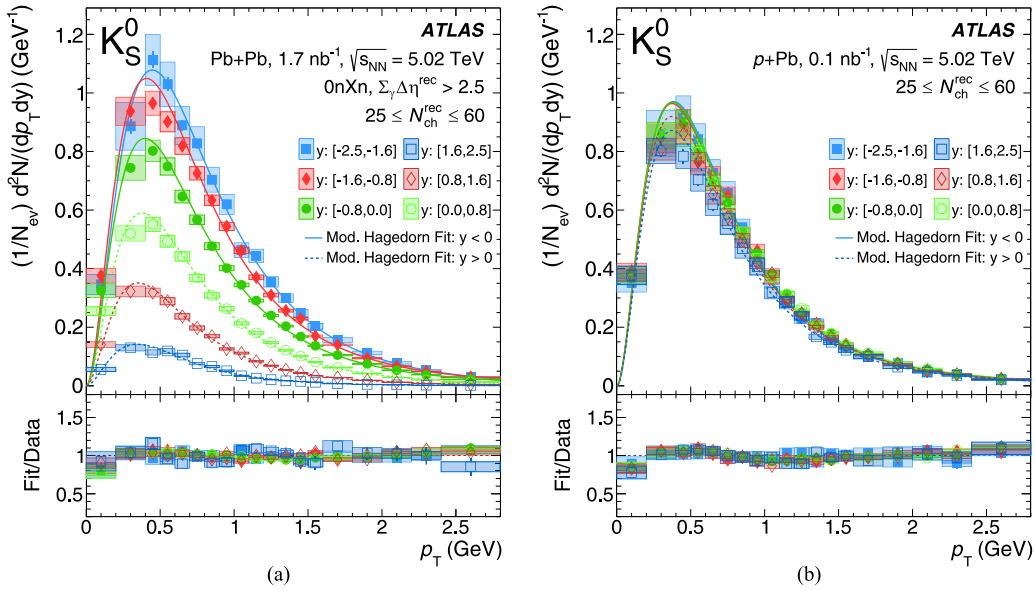


FIG. 4. K^0_S yields as a function of p_T in different y selections in (a) Pb+Pb photonuclear and (b) p + Pb collisions. The bottom panels show the ratio of the Modified Hagedorn fit results to the data. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

(ii) The χ^2 of the two-track vertex fit for reconstructing both Λ and Ξ^- is required to be less than 15 (with one degree of freedom).
(iii) The cosine of the pointing angle ($\cos\theta$) associated with Ξ^- vertex is required to be greater than 0.9992.
(iv) The cosine of the pointing angle associated with Λ vertex is required to be greater than 0.99999.
(v) Requirements on the minimum values of the variables $|\frac{L_{xy}}{\sigma_{L_{xy}}}|$ associated with vertex fit for reconstructing Λ and Ξ^-, in bins of p_T and y, determined using the TMVA package as above.

Below the minimum p_T value for Λ and Ξ^-, the efficiency is very low due to the slow pions. In contrast, the K^0_S can be measured down to $p_T = 0$ GeV. The tight selection criteria for the pointing angle and the minimum value of $|\frac{L_{xy}}{\sigma_{L_{xy}}}|$ significantly improve the signal significance in all kinematic regions.

Figure 2 shows the resulting invariant-mass distributions for K^0_S, Λ, and Ξ^- in Pb+Pb photonuclear collisions. The

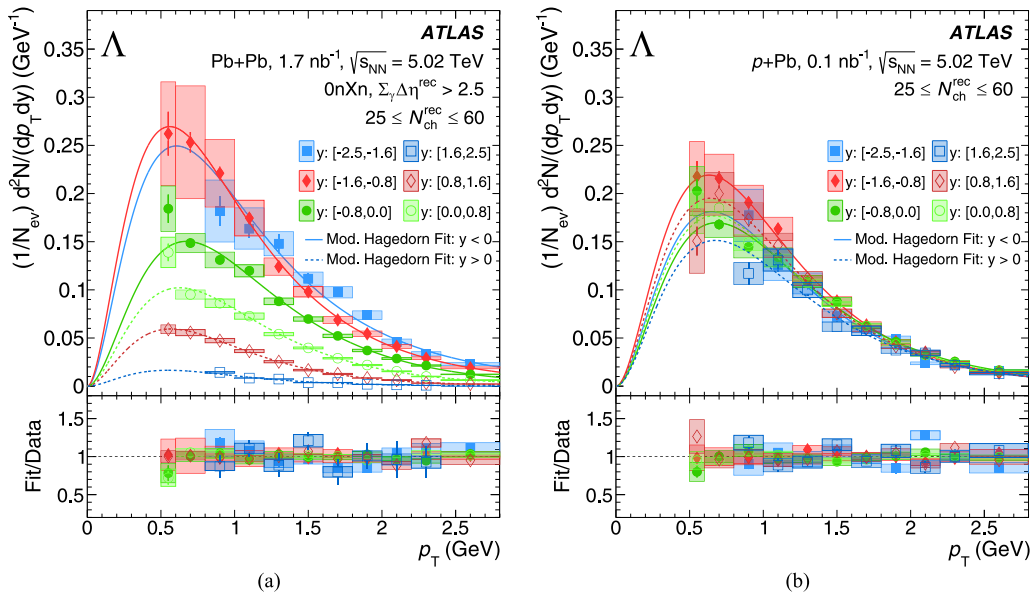


FIG. 5. Λ yields as a function of p_T in different y selections in (a) Pb+Pb photonuclear and (b) p + Pb collisions. The bottom panels show the ratio of the Modified Hagedorn fit results to the data. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

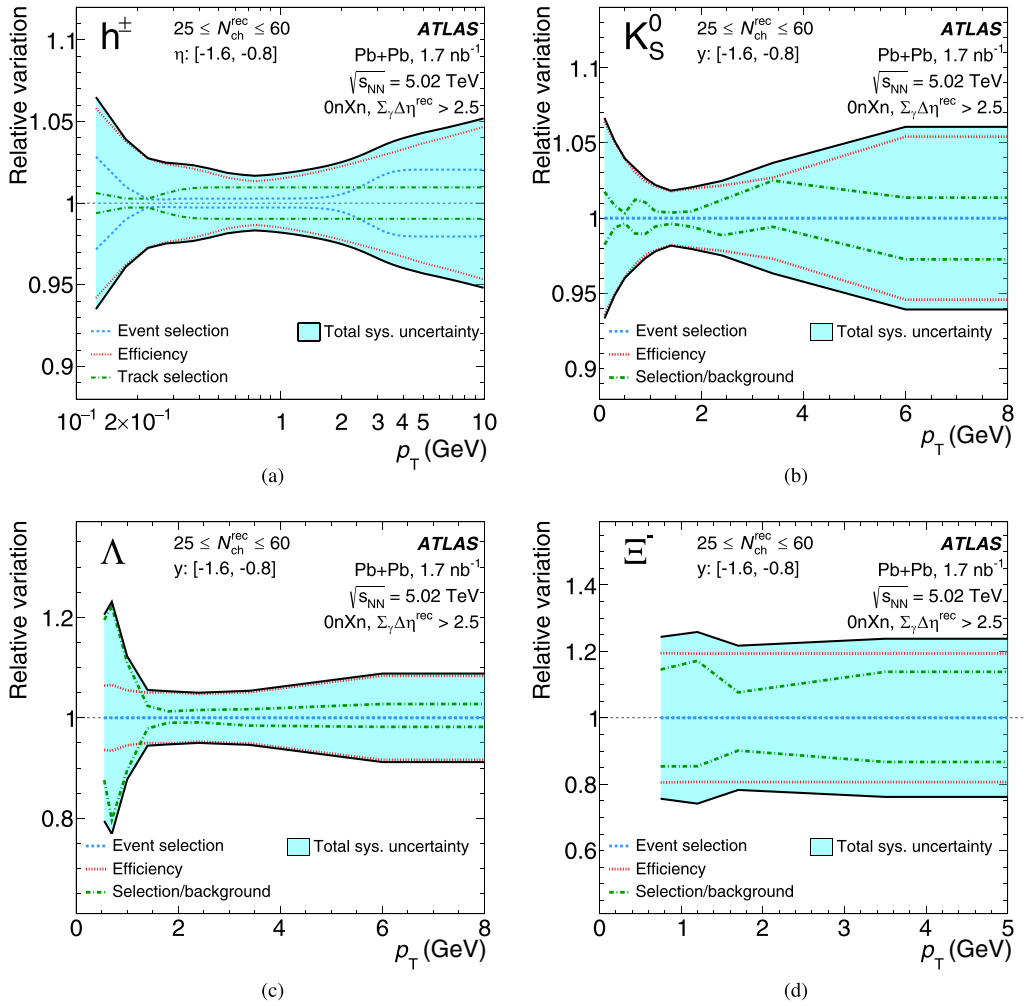


FIG. 6. Relative systematic uncertainties in (a) charged hadrons, (b) K^0_S, (c) Λ, and (d) Ξ^- yields in photonuclear collisions as a function of p_T . All uncertainty contributions are added in quadrature and the result is symmetrized to obtain the full systematic uncertainty.

number of signal candidates in a given p_T and y bin is determined by fitting the invariant-mass distribution of the strange hadron candidates in that bin. The fit utilizes a double Gaussian for the signal peak and a second-order (third-order for Λ) polynomial for the combinatorial background. The background component also includes a functional form modeling the cases where the particles are mis-identified, e.g., a truth K^0_S that has its decay products fit under the assumption of a parent Λ particle. These functional forms are determined from DPMJET-III MC. The ratio of the widths and amplitudes of the two Gaussian distributions is constrained based on the MC truth-matched invariant-mass distributions within the corresponding p_T-y bin. The fit ranges utilized in this analysis are [420, 580] MeV for K^0_S, [1080, 1170] MeV for Λ, and [1280, 1360] MeV for Ξ^-. The quality of the fit is evaluated based on reasonable χ^2 values.

The signal candidates, obtained in bins of p_T and y, are corrected for reconstruction and selection inefficiencies, using Eq. (3) on the secondary vertex candidates, and for signal inefficiency, which accounts for the missed fraction of reconstructed candidates due to the TMVA-optimized selection requirements. Furthermore, signal candidates are corrected for the contributions of secondaries, as defined by Eq. (4). The largest sources of secondaries are from hadronic interactions of particles with the detector material and the decay products of heavier strange baryons, which contribute to the Λ yield at the 10% level [47]. Figure 3 shows the reconstruction efficiencies for K^0_S, Λ, and Ξ^- calculated using DPMJET-III γ + Pb simulations. High-p_T neutral strange particles start to have a sufficiently large relativistic boost that the decay occurs after some of the silicon-detector components, leading to missing hits and an efficiency drop.

The corrected number of signal candidates is used to calculate the identified-hadron yield as a function of p_T in different rapidity bins using Eq. (1), and as a function of y using Eq. (2).

The minimum p_T values are 0 GeV for K^0_S, and 0.5 GeV for Ξ^-. For Λ, the minimum p_T is 0.5 GeV for $|y| < 1.6$ and 0.8 GeV for $1.6 < |y| < 2.5$. Thus the p_T-integrated yields for K^0_S are simply calculated by summing the yields as a function of p_T, whereas for Λ and Ξ^- the yield below the minimum p_T must be accounted for. Hence, an extrapolation procedure is performed for Λ and Ξ^-, using the Modified Hagedorn functional fit, given by Eq. (5). Figures 4 and 5 show the K^0_S and Λ

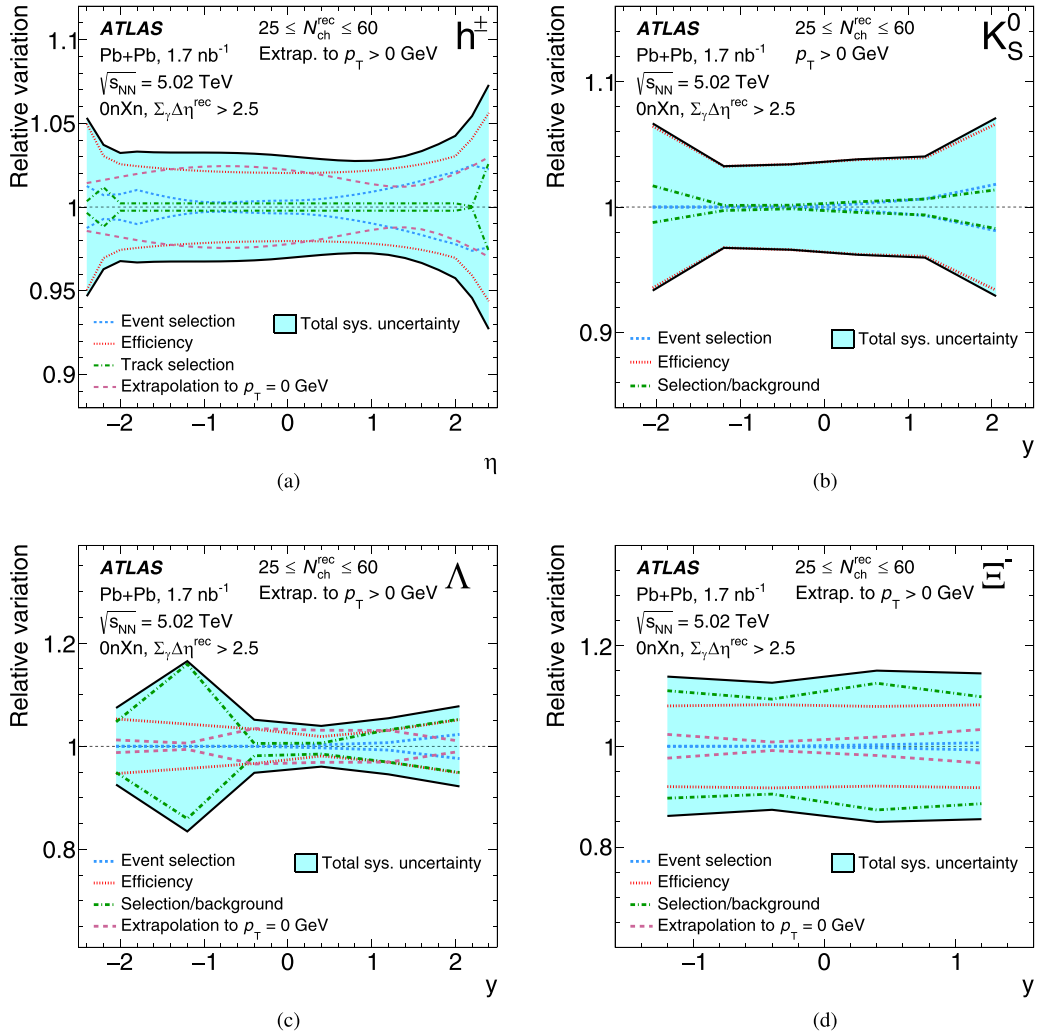


FIG. 7. Relative systematic uncertainties in (a) charged hadrons, (b) K^0_S, (c) Λ, and (d) Ξ^- yields in photonuclear collisions as a function of (pseudo) rapidity. The yield of K^0_S is measured down to $p_T = 0$ GeV. For charged hadrons, Λ and Ξ^-, the measured yield is extrapolated to $p_T = 0$ GeV. All uncertainty contributions are added in quadrature and the result is symmetrized to obtain the full systematic uncertainty.

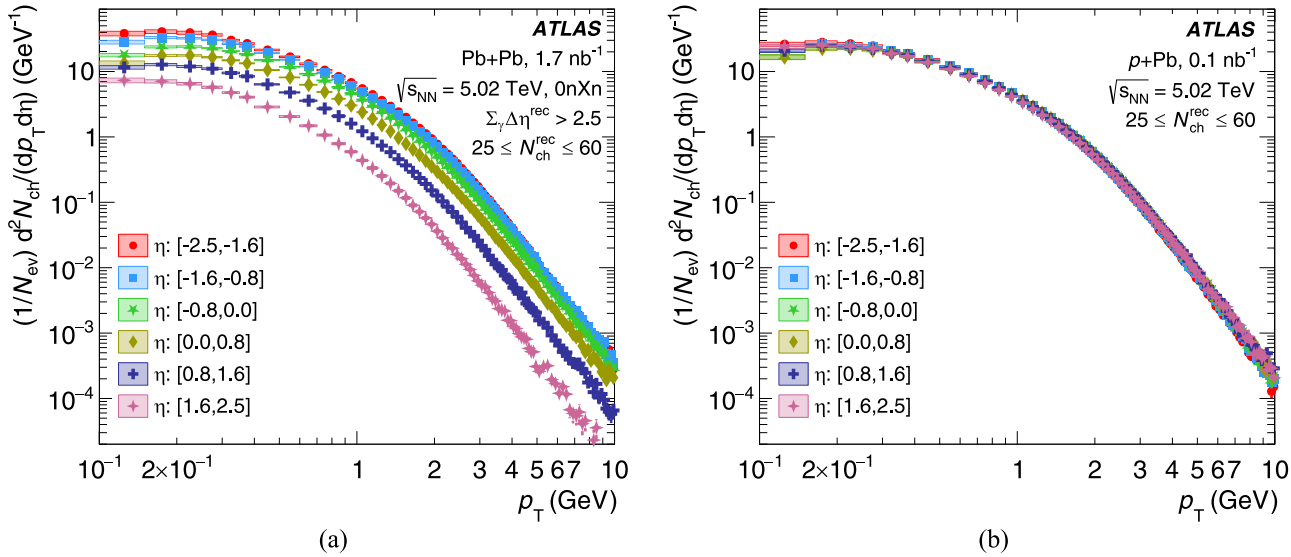


FIG. 8. Charged-hadron yields as a function of p_T in six η selections for (a) Pb+Pb photonuclear and (b) p + Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

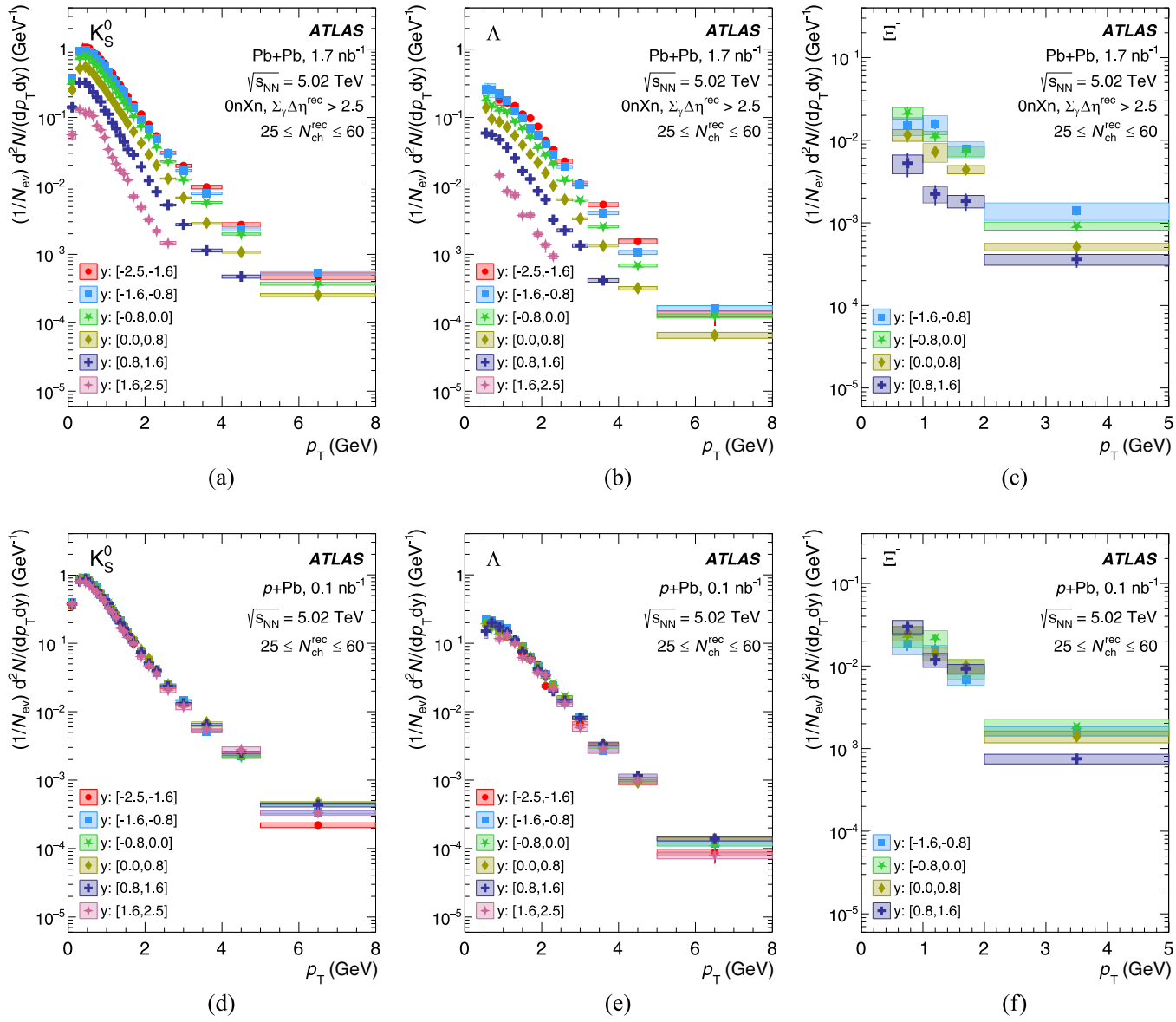


FIG. 9. (a) K_S^0, (b) Λ, and (c) Ξ^- yields are shown as a function of p_T in six y selections in Pb+Pb photonuclear collisions. The (d) K_S^0, (e) Λ, and (f) Ξ^- yields are shown as a function of p_T in six y selections in p + Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

yields in Pb+Pb photonuclear and p + Pb collisions as a function of p_T across six y selections, with the Modified Hagedorn fit results. The fit to the K_S^0 yield, where measurements extend down to $p_T = 0$ GeV, shows that the function provides a good description of the data. This confirms that the same fit function can be used to extrapolate the Λ and Ξ^- yields down to $p_T = 0$ GeV. The fit is performed using statistical uncertainties only and is then repeated for each systematic uncertainty variation. Approximately 20% of the total yield lies in the region of extrapolation ($p_T < 0.5$ GeV) for Λ, and is larger for the most forward/backward rapidities (where $p_T < 0.8$ GeV). Approximately 20–30% of the total yield lies in the region of extrapolation ($p_T < 0.5$ GeV) for Ξ^-. Systematic uncertainties on these extrapolations, and from other sources, are discussed below.

Finally, using the p_T-integrated yields determined above, the $\langle p_T \rangle$ and the ratio of strange-hadron to charged-hadron yields are calculated as a function of N_{ch}^{rec}. These values are calculated after extrapolating down to $p_T = 0$ GeV.

V. SYSTEMATIC UNCERTAINTIES

The sources of systematic uncertainties in this measurement are described in the following. For the event selection criteria in Pb+Pb photonuclear events, the primary sources contributing to both the charged-hadron and identified-hadron yields include uncertainties associated with the purity estimation and pseudorapidity gap selection. In both Pb+Pb photonuclear and p + Pb collisions, uncertainties are assigned to track selection by relaxing specific hit requirements in turn,

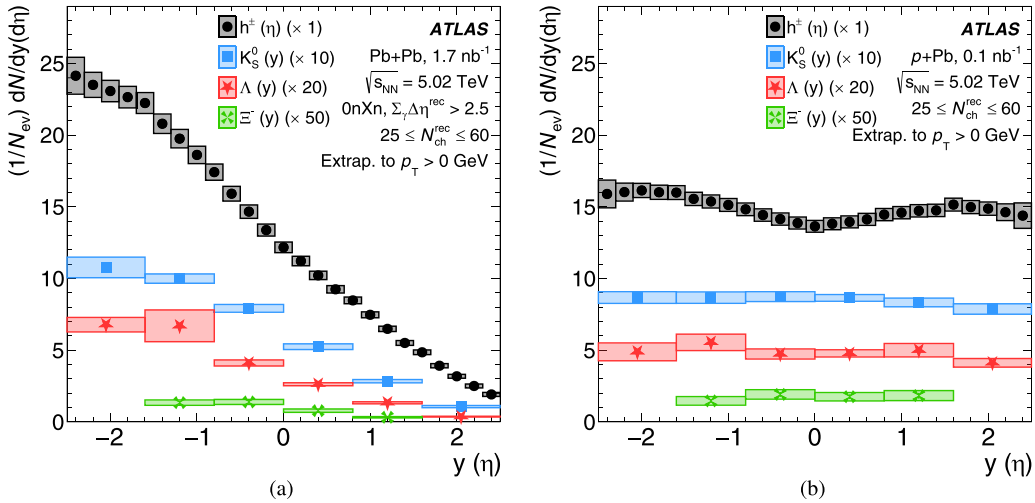


FIG. 10. Charged-hadron yields as a function of η and the K^0_S, Λ, and Ξ^- yields as a function of y for (a) Pb+Pb photonuclear and (b) $p+$Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

to contributions from fake and secondary tracks by varying f_{primary} in Eq. (4) by 50% of the rate, and to the mis-modeling of the detector material [38,48]. An uncertainty is also assigned for bin migration due to track momentum resolution. This bin migration effect is quite small and the uncertainty is set by turning off the bin migration entirely. Furthermore, uncertainties on the fit values of the track reconstruction efficiency are included as systematic uncertainties.

For the identified-hadron analysis, specific uncertainties are assigned to the selection requirements by varying the specific requirements from the nominal values. The uncertainty in the signal extraction is further quantified by varying the fit range of invariant-mass distributions. Finally, to assess the uncertainty in the extrapolation to $p_{\text{T}} = 0$ GeV, a varied fit functional form for the p_{T} distribution based on Tsallis statistics [49] is utilized. The fitting procedure is redone for all other systematic variations.

In all cases, the ratio of the varied to nominal result is either smoothened via fit or directly used, and the values are assigned as the systematic uncertainty. All uncertainty contributions are added in quadrature and then symmetrized by taking the maximum variation at each point to determine the total systematic uncertainty. Other potential sources of uncertainty, such as those related to the trigger efficiency [10], were found to be negligible compared to the ones described above.

Figures 6 and 7 present the relative systematic uncertainties on charged hadrons, K^0_S, Λ, and Ξ^- yields in photonuclear collisions as a function of p_{T} and (pseudo)rapidity, respectively. The dominant uncertainty in the low p_{T} region ($p_{\text{T}} <$ 1 GeV) arises from variations in the detector materials and bin-migration effects. For identified hadrons, in addition to these uncertainties, the uncertainty in the background correction contributes significantly. For the $\langle p_{\text{T}} \rangle$ calculation, the total uncertainties are on the order of 3–5%. As a function of rapidity, a significant uncertainty for charged hadrons and Λ, Ξ^- particles comes from the extrapolation of the yield down to $p_{\text{T}} = 0$ GeV. For the K^0_S there is no such uncertainty as the yield is measured down to $p_{\text{T}} = 0$ GeV. The uncertainty is dominated by systematic rather than statistical effects.

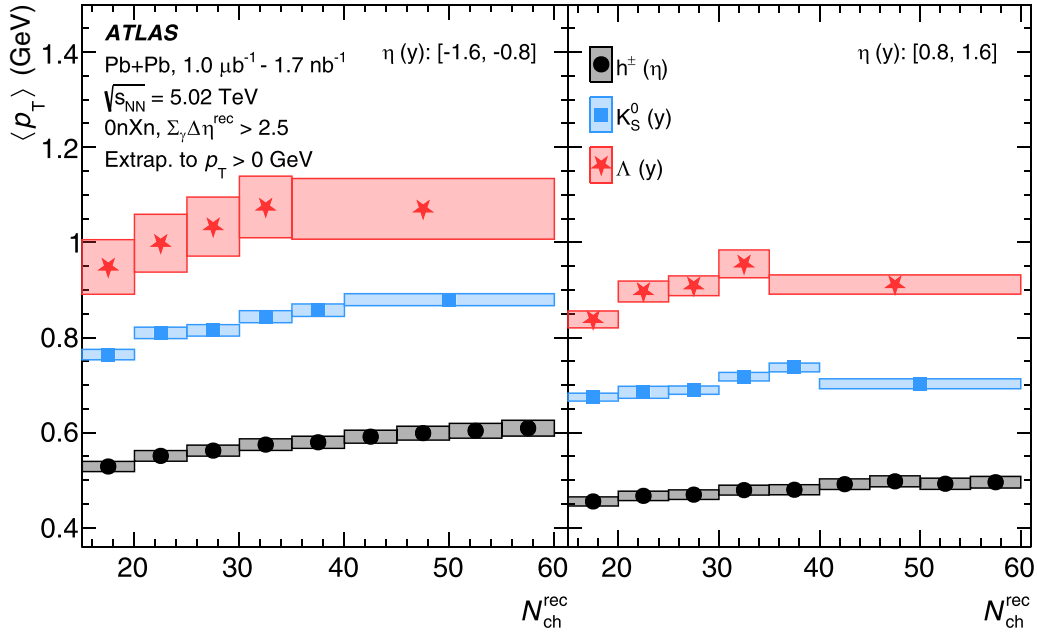
VI. RESULTS

The resulting yields as a function of p_{T} for charged hadrons are shown in Fig. 8 in six pseudorapidity selections spanning $-2.5 < \eta < 2.5$ in Pb+Pb photonuclear and $p+$Pb collisions. The yields are calculated for collisions with $25 \leqslant N^{\text{rec}}_{\text{ch}} \leqslant 60$, with the $p+$Pb $N^{\text{rec}}_{\text{ch}}$ distribution reweighted to match that of the photonuclear collision sample. The photonuclear collision yields have a strong pseudorapidity dependence, with much lower multiplicity in the photon-going direction (positive η). In contrast, the $p+$Pb collision yields are nearly η-symmetric. Unlike in more central $p+$Pb collisions [50], the yields in the low-multiplicity selection ($25 \leqslant N^{\text{rec}}_{\text{ch}} \leqslant 60$) are symmetric in rapidity; hence, the η distribution is more pp-like.

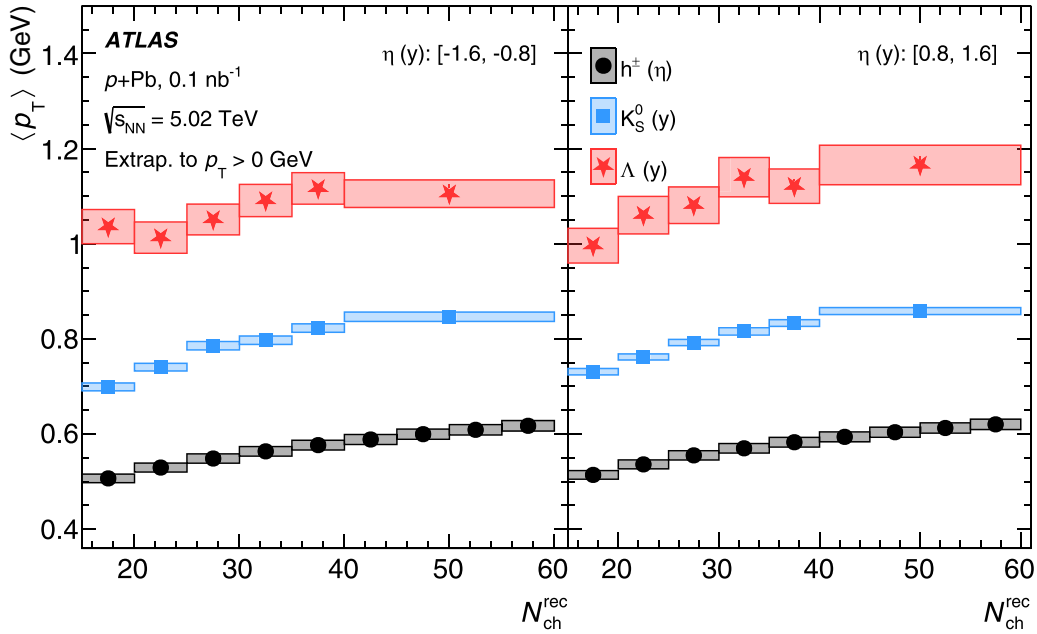
Figure 9 shows the yields as a function of p_{T} for identified strange hadrons K^0_S, Λ, and Ξ^- in six rapidity selections spanning $-2.5 < y < 2.5$ in Pb+Pb photonuclear and $p+$Pb collisions for the same event selection as the charged-hadron yields. The Λ and Ξ^- yields are for baryons only and are not the average of baryons and antibaryons. The Λ yields include decays from Σ_0, but otherwise are not inclusive of other baryon feed-down contributions, e.g., from Ξ^- and Ω. As in the charged-hadron case, the yields of all strange hadrons have a strong rapidity dependence in photonuclear collisions.

The yields as a function of p_{T} are then integrated over the p_{T} range of the measurements, and extrapolated to be inclusive over all p_{T}, i.e., $p_{\text{T}} > 0$. The resulting p_{T}-integrated yields as a function of pseudorapidity, for charged hadrons, and rapidity, for identified strange hadrons are shown in Fig. 10. The p_{T}-integrated yields again show a strong rapidity asymmetry in photonuclear collisions and are nearly rapidity symmetric in $p+$Pb collisions.

Next, the p_{T} distributions are characterized in terms of the $\langle p_{\text{T}} \rangle$, calculated to correspond to the mean value for $p_{\text{T}} > 0$.



(a)



(b)

FIG. 11. $\langle p_T \rangle$ for charged hadrons, K^0_S, and Λ in (a) Pb+Pb photonuclear and (b) p + Pb collisions as a function of N^{rec}_{ch}. The left (right) panels are for a backward (forward) rapidity interval. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

These $\langle p_T \rangle$ values for charged hadrons, K^0_S, and Λ particles, in two rapidity intervals, as a function of finer intervals of N^{rec}_{ch} are shown in Fig. 11. The top (bottom) subfigures correspond to photonuclear Pb+Pb (p + Pb) collisions, with the left (right) panels corresponding to backward (forward) rapidity. In both photonuclear and p + Pb collisions, the $\langle p_T \rangle$ increases with increasing N^{rec}_{ch} and there is a distinct ordering with $\langle p_T \rangle$ (charged hadrons) < $\langle p_T \rangle$ (K^0_S) < $\langle p_T \rangle$ (Λ). Under the assumption that charged hadrons are dominated by pions, the pattern follows a distinct mass ordering. In photonuclear collisions, the $\langle p_T \rangle$ show a large rapidity asymmetry, with much lower values for all particles at forward rapidity. In contrast, the p + Pb results are consistent with being rapidity symmetric.

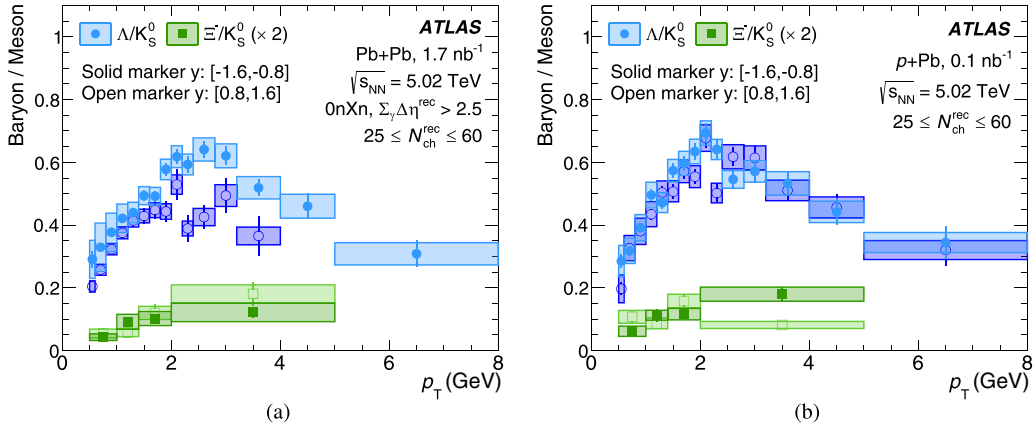


FIG. 12. Ratio of Λ/K^0_S and Ξ^-/K^0_S yields as a function of p_T in two rapidity intervals for (a) Pb+Pb photonuclear and (b) $p+\text{Pb}$ collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

For the Ξ^-, the $\langle p_T \rangle$ can only be calculated in one selection of N^{rec}_{ch}, $25 \leqslant N^{rec}_{ch} \leqslant 60$, and correspond to values of $1.60 \pm 0.02(\text{stat}) \pm 0.24(\text{sys})$ GeV $[1.04 \pm 0.01(\text{stat}) \pm 0.12(\text{sys})$ GeV] for photonuclear collisions and $1.33 \pm 0.03(\text{stat}) \pm 0.18(\text{sys})$ GeV $[1.06 \pm 0.02(\text{stat}) \pm 0.25(\text{sys})$ GeV] for $p+\text{Pb}$ collisions, at backward (forward) rapidity. These values suggest that the Ξ^- may have a slightly higher $\langle p_T \rangle$ than Λ particles, although consistent within large uncertainties.

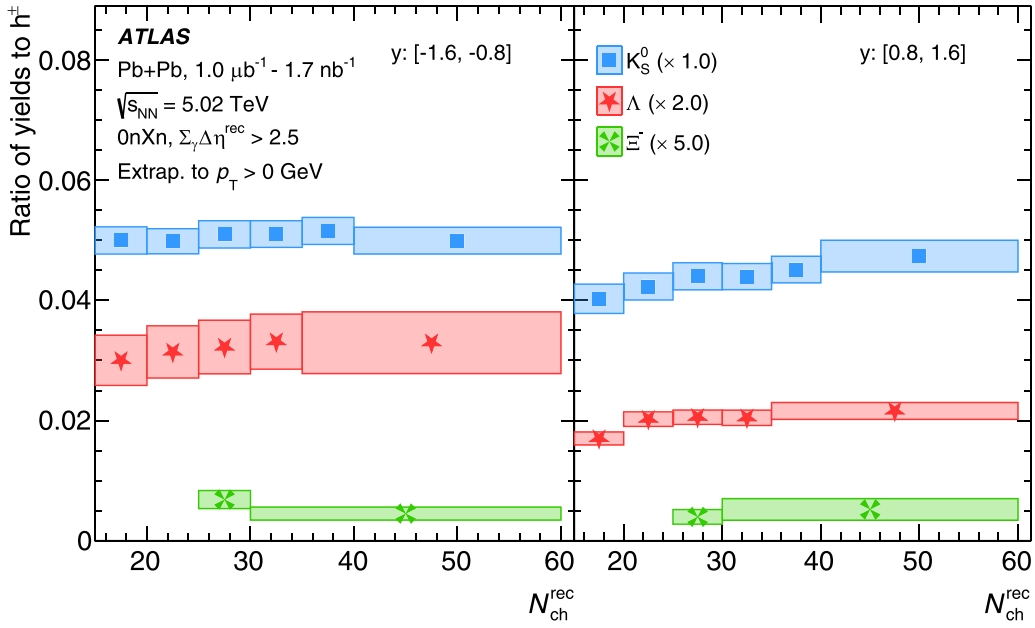
To further elucidate the data trends, the ratios of Λ/K^0_S and Ξ^-/K^0_S as a function of p_T, for two rapidity intervals, in Pb+Pb photonuclear and $p+\text{Pb}$ collisions are shown in Fig. 12. The most striking observation is the larger Λ/K^0_S ratio at intermediate $p_T \approx 1.5$–4.0 GeV when measured at backward rapidity compared to forward rapidity in photonuclear collisions. This baryon enhancement at intermediate p_T is reminiscent of the "baryon anomaly" observed in $p+\text{Pb}$ and Pb+Pb collisions [51] and is often associated with quark recombination as the dominant hadronization mechanism [52]. The ratios in $p+\text{Pb}$ in both rapidity intervals are comparable to the backward rapidity photonuclear values. For the Ξ^-, the uncertainties preclude any strong conclusions.

Finally, the ratio of identified-strange-hadron yields relative to charged-hadron yields is calculated as a function of N^{rec}_{ch}. The resulting ratios at backward and forward rapidities are shown as a function of N^{rec}_{ch} in Fig. 13 for photonuclear and $p+\text{Pb}$ collisions. In photonuclear collisions, there is a clear increase in strange hadron yields relative to charged hadrons between backward and forward rapidity. If there is strangeness enhancement due to final-state interactions, this would be consistent with the larger ratios in the Pb-going direction. The ratios are similar between backward rapidity photonuclear yields and the $p+\text{Pb}$ yields in both rapidity intervals. Overall, the ratios are generally consistent with being flat, i.e., not exhibiting an N^{rec}_{ch} dependence over the given range, with a hint of a rise in the Λ to charged-hadron ratios. It is notable that the large strangeness enhancement observed in pp, $p+\text{Pb}$, and Pb+Pb collisions in Ref. [15] is actually quite small for K^0_S and Λ in the multiplicity range corresponding to the measurements presented here.

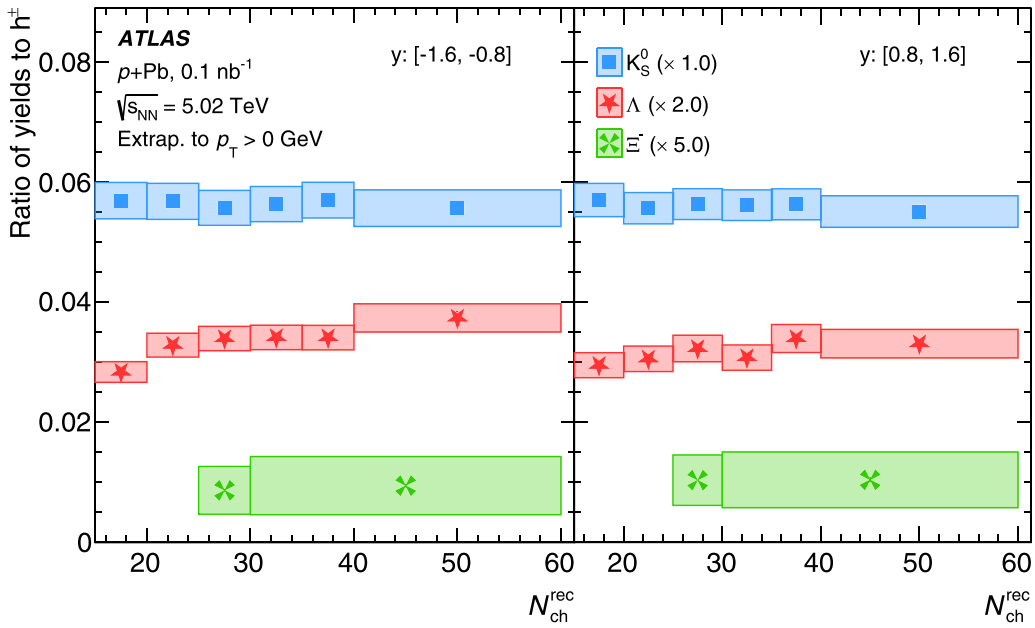
VII. DISCUSSION

These experimental results are now compared with DPMJET-III MC for photonuclear collisions and HIJING for $p+\text{Pb}$ collisions, respectively, neither of which includes any final-state interactions or QGP formation. Comparisons are also made to the so-called "hybrid" model that explicitly includes a hydrodynamic modeling of QGP formation in both photonuclear and $p+\text{Pb}$ collisions [11]. The hybrid model incorporates initial conditions by an extension of MC Glauber to three-dimensions, time evolution via viscous hydrodynamics using the publicly available package MUSIC [53], and finally hadronic scattering via the publicly available package URQMD [54]. For the photonuclear case, following Ref. [9], a parametrization is used for the photon energy and hence the center-of-mass energy distribution. The $\gamma+\text{Pb}$ collisions are treated via the vector meson dominance picture, i.e., the virtual photon state may be decomposed into a set of vector meson states, like ρ, ω, and ϕ, in a low virtuality regime, $Q^2 = 0.0625$ GeV^2. The virtual photon is treated as a vector meson with two "partonic participants" in the MC Glauber calculation (in contrast to the three "partonic participants" for the proton projectile in the $p+\text{Pb}$ case).

When making such comparisons to the data, the event selection criteria used here are important to incorporate. In particular, the yields presented here are characterized by specific N^{rec}_{ch} intervals, e.g., $25 \leqslant N^{rec}_{ch} \leqslant 60$. As discussed earlier, MC studies indicate that the selections on N^{rec}_{ch} correspond to equivalent selections on truth-level charged particles with $p_T > 0.4$ GeV and $|\eta| < 2.5$ as well, but with an average value of $N^{truth}_{ch} \approx 1.2 \times N^{rec}_{ch}$. Each event is additionally characterized by the sum-of-gaps using reconstructed tracks and energy clusters. Monte Carlo studies indicate that this selection corresponds to equivalent selections on truth-level particles with $p_T > 0.45$ GeV and $|\eta| < 4.9$. Differences between the reconstruction and truth level selections are less than 2–3%. For the DPMJET-III and HIJING simulations, the exact event selection criteria used in this measurement are applied through a full GEANT4 simulation of the detector



(a)



(b)

FIG. 13. Ratios of identified-strange-hadron yields to charged-hadron yields as a function of N_{ch}^{rec} for (a) Pb+Pb photonuclear collisions and (b) $p+\text{Pb}$ collisions. The left (right) panels are for a backward (forward) rapidity interval. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

response and reconstruction, i.e., to match the experimental event selection of N_{ch}^{rec} and $\sum_\gamma \Delta\eta^{rec}$. Once an event satisfies these criteria, its truth-level particles are included in the yield calculation. In the hybrid model case, the model framework was calibrated with $p+\text{Pb}$ measurements at a center-of-mass energy of 5.02 TeV and then made predictions for $\gamma+\text{Pb}$ collisions.

Figure 14 shows the measured charged hadron, K^0_S, Λ, and Ξ^- yields as a function of rapidity, compared to MC results from DPMJET-III for photonuclear collisions and HIJING for $p+\text{Pb}$ collisions. Both calculations describe the charged hadron and K^0_S rapidity dependence and the overall normalization at the 15–25% level. In contrast, the Λ and Ξ^- yields are poorly described with HIJING under-predicting the strange

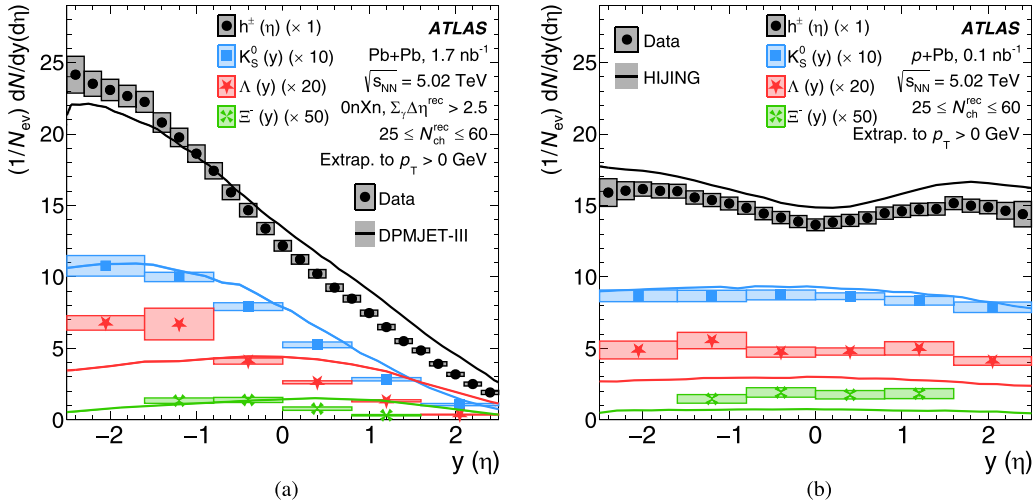


FIG. 14. Charged-hadron yields as a function of η and the K^0_S, Λ, and Ξ^- yields as a function of y for (a) Pb+Pb photonuclear collisions, with comparisons to the MC model DPMJET-III, and (b) $p+$Pb collisions, with comparisons to HIJING. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes. The statistical uncertainties in the MC simulations are represented by colored bands, though they are negligible.

baryon yields by almost a factor of two and DPMJET-III over-predicting the yields at forward rapidity and under-predicting at backward rapidity.

Figure 15 shows the same ATLAS results now compared with calculations from the hybrid model. The charged-hadron yields are well described in $p+$Pb collisions, and only qualitatively described in photonuclear collisions. For both collision systems, the K^0_S are over-predicted, the Λ under-predicted, and the Ξ^- well described. Since the level of disagreement for strange hadrons (K^0_S and Λ) is similar in both $p+$Pb and photonuclear collisions, it is likely a generic failing of the modeling for strangeness and/or baryons in general in the hadronization of the hydrodynamic QGP.

It is also instructive to compare the experimental results for $\langle p_T \rangle$ as a function of N^{rec}_{ch} as shown in Fig. 16 with the MC models DPMJET-III and HIJING and Fig. 17 with the hybrid model. Both MC models substantially under-predict the $\langle p_T \rangle$ for all particles, and also under-predict the difference in $\langle p_T \rangle$ between hadrons of different masses. Strikingly, DPMJET-III predicts a higher $\langle p_T \rangle$ for Λ particles at forward rapidity compared to backward rapidity, exactly opposite to the trend in data.

In contrast, the hybrid model provides a reasonable description of the $\langle p_T \rangle$ of charged hadrons and Λ particles in both photonuclear and $p+$Pb collisions, including the higher $\langle p_T \rangle$ values at backward rapidity compared to forward rapidity in photonuclear collisions. However, the $\langle p_T \rangle$ values for K^0_S

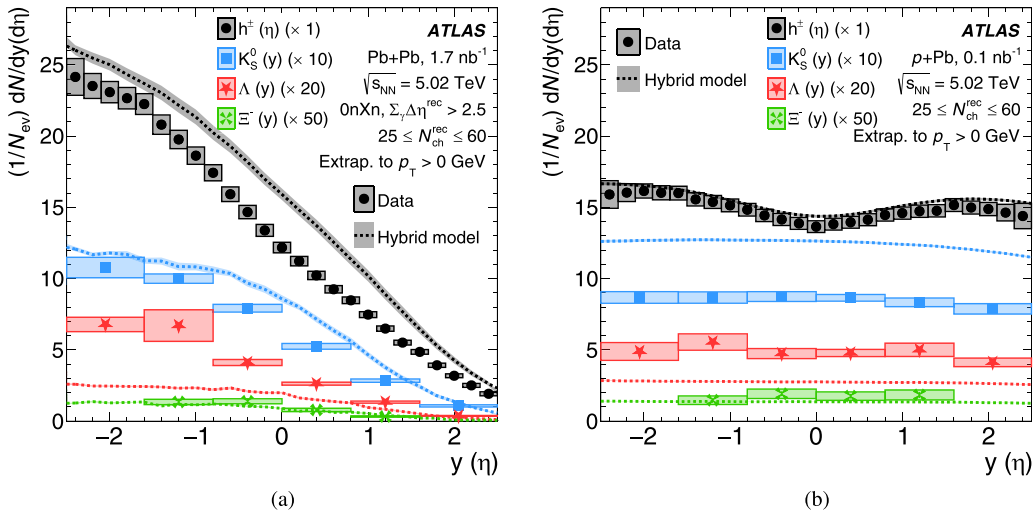
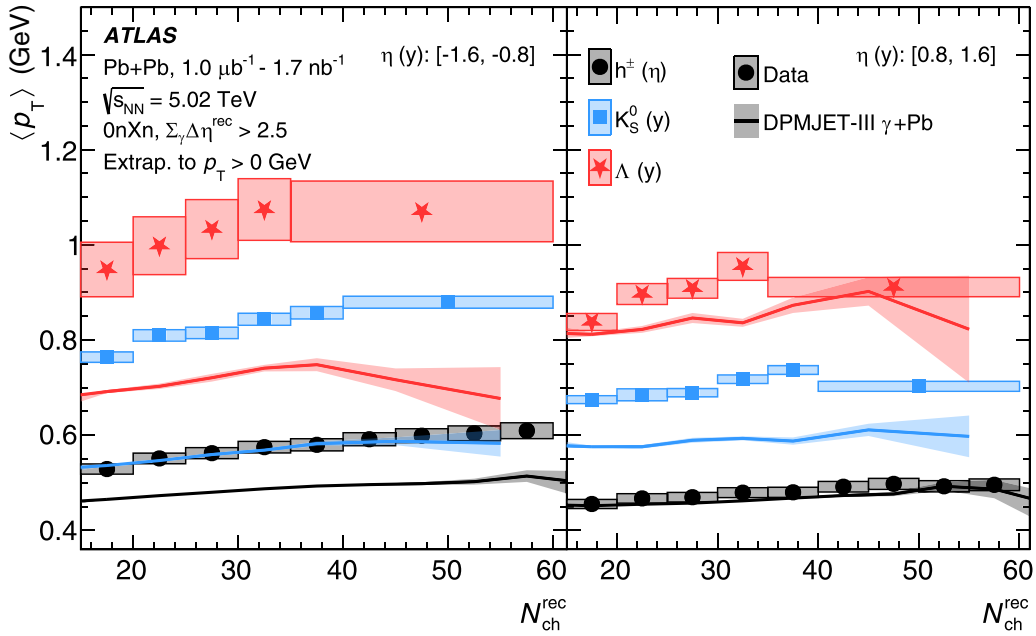
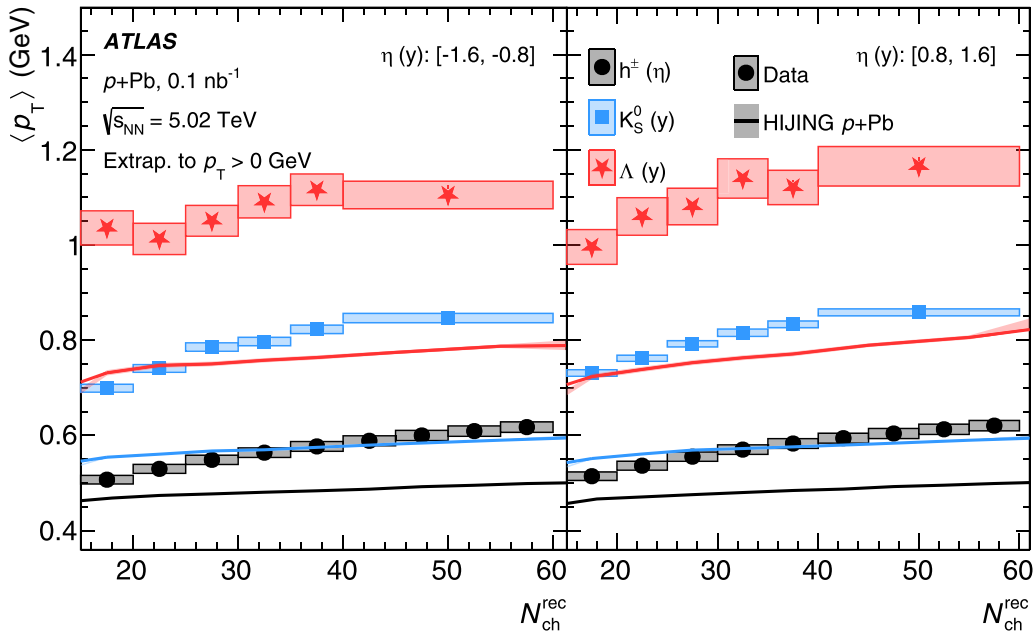


FIG. 15. Charged-hadron yields as a function of η and the K^0_S, Λ, and Ξ^- yields as a function of y for (a) Pb+Pb photonuclear collisions and (b) $p+$Pb collisions. Both are compared to the hybrid model calculations. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes. The statistical uncertainties of the model calculations are shown by colored bands.



(a)



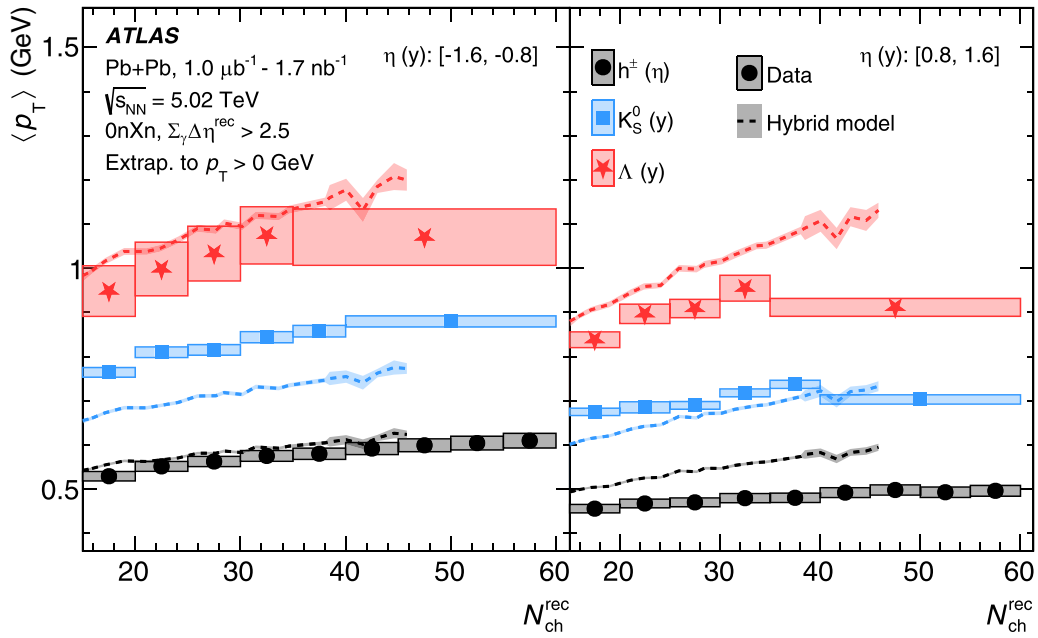
(b)

FIG. 16. $\langle p_T \rangle$ for charged hadrons, K^0_S, and Λ in (a) Pb+Pb photonuclear and (b) p + Pb collisions as a function of N^{rec}_{ch}. The left (right) panels are for a backward (forward) rapidity selection. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes. Also shown are comparisons to the MC model DPMJET-III and HIJING for Pb+Pb photonuclear and p + Pb collisions, respectively, with the shaded bands indicating the statistical uncertainties.

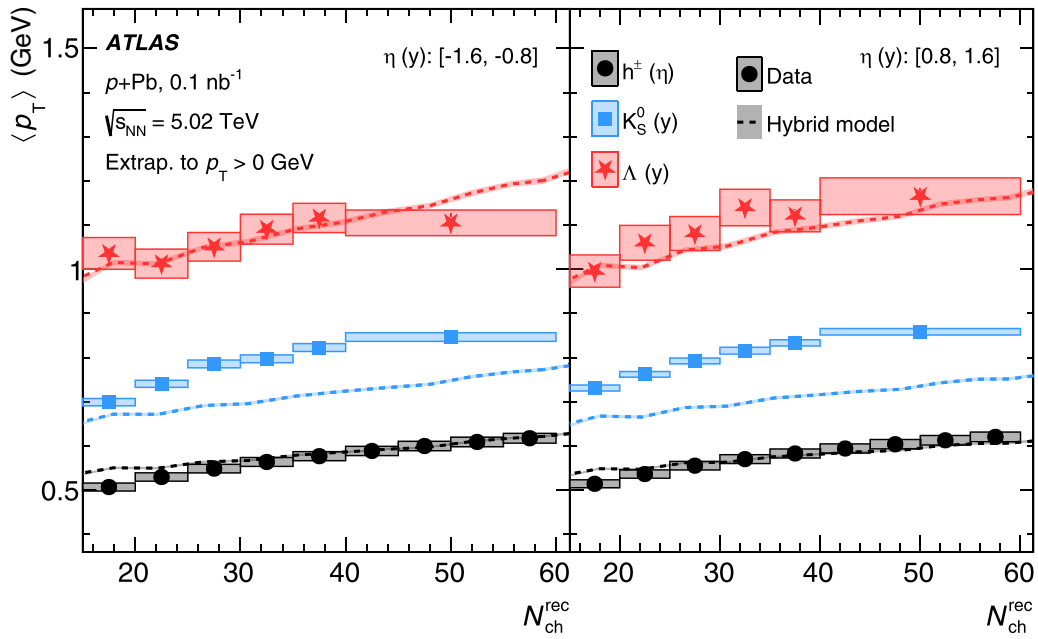
are under-predicted in all cases. Until these deficiencies in the hybrid model are resolved, first in the p + Pb case, stronger conclusions regarding QGP formation in photonuclear events remains premature.

VIII. CONCLUSION

This paper reports a measurement of the yields of charged hadrons and identified K^0_S, Λ, Ξ^- in high-energy photonuclear collisions. Events are selected from 1.7 nb^{-1} of



(a)



(b)

FIG. 17. $\langle p_T \rangle$ for charged hadrons, K^0_S, and Λ in (a) Pb+Pb photonuclear and (b) $p+$Pb collisions as a function of N^{rec}_{ch}. The left (right) panels are for a backward (forward) rapidity selection. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes. Also shown are comparisons to the hybrid hydrodynamic model for both collision types.

$\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb data collected by the ATLAS detector at the LHC in 2018. The yields are measured as a function of p_T and rapidity for different N^{rec}_{ch} intervals. The results are compared with $p+$Pb collision data at comparable N^{rec}_{ch} intervals. These photonuclear events reveal a strong rapidity asymmetry in all particle yields, with fewer particles in the photon-going direction as expected. In the Pb-going direction, the particles exhibit larger average transverse momentum that increases for higher mass particles. There is also a significant enhancement of the Λ/K^0_S (baryon/meson) ratio, and a hint of an enhancement of overall strange particle production. These observations in the Pb-going direction are generally consistent with what is observed in the $p+$Pb Pb-going direction, giving credence to the

hypothesis that the photonuclear collisions are dominated by vector meson dominance, i.e., hadronic ρ meson–Pb collisions. Comparisons with MC models reveal a very incomplete modeling of the physics processes. The hybrid model, based on the assumption of QGP formation and hydrodynamic expansion, captures some features such as the larger mean p_{T} at backward rapidity in photonuclear events, but fails to quantitatively describe the yields of identified strange particles.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide, and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [55]. We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, USA. Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. In addition, individual members acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN DOCT); Chile: Agencia Nacional de Investigación y Desarrollo (Grants No. FONDECYT 1230812, No. FONDECYT 1230987, and No. FONDECYT 1240864); China: Chinese Ministry of Science and Technology (Grants No. MOST-2023YFA1605700 and No. MOST-2023YFA1609300), National Natural Science Foundation of China (Grants No. NSFC 12175119 and No. NSFC 12275265); Czech Republic: Czech Science Foundation (Grant No. GACR 24-11373S), Ministry of Education Youth and Sports (ERC-CZ-LL2327, FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (Grant No. ERC 101002463); European Union: European Research Council (Grants No. ERC 948254, No. ERC 101089007, and No. ERC, BARD, 101116429), European Regional Development Fund (SMASH COFUND 101081355, SLO ERDF), Horizon 2020 Framework Programme (MUCCA—CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Horizon 2020 (EuroHPC—EHPC-DEV-2024D11-051), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (Grants No. ANR-21-CE31-0013, No. ANR-21-CE31-0022, and No. ANR-22-EDIR-0002); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (Grants No. DFG-469666862 and No. DFG-CR 312/5-2); China: Research Grants Council (GRF); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (NextGenEU PRIN20223N7F8K M4C2.1.1); Japan: Japan Society for the Promotion of Science (Grants No. JSPS KAKENHI JP22H01227, No. JSPS KAKENHI JP22H04944, No. JSPS KAKENHI JP22KK0227, and No. JSPS KAKENHI JP23KK0245); Norway: Research Council of Norway (Grant No. RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 No. 9722), Polish National Science Centre (Grants No. NCN 2021/42/E/ST2/00350, No. NCN OPUS 2023/51/B/ST2/02507, No. NCN OPUS nr 2022/47/B/ST2/03059, No. NCN UMO-2019/34/E/ST2/00393, No. UMO-2020/37/B/ST2/01043, No. UMO-2022/47/O/ST2/00148, No. UMO-2023/49/B/ST2/04085, No. UMO-2023/51/B/ST2/00920, and No. UMO-2024/53/N/ST2/00869); Portugal: Foundation for Science and Technology (FCT); Spain: Generalitat Valenciana (Artemisa, FEDER, Grant No. IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU Grant No. PCI2022-135018-2, MICIN & FEDER Grants No. PID2021-125273NB, No. RYC2019-028510-I, No. RYC2020-030254-I, No. RYC2021-031273-I, and No. RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS Grant No. 22:2312), Swedish Research Council (Swedish Research Council Grants No. 2023-04654, No. VR 2021-03651, No. VR 2022-03845, No. VR 2022-04683, No. VR 2023-03403, No. VR 2024-05451), Knut and Alice Wallenberg Foundation (Grants No. KAW 2018.0458, No. KAW 2022.0358, and No. KAW 2023.0366); Switzerland: Swiss National Science Foundation

(Grant No. SNSF PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust Grant No. RPG-2020-004), Royal Society (Grant No. NIF-R1-231091); United States of America: U.S. Department of Energy (Grant No. ECA DE-AC02-76SF00515), Neubauer Family Foundation.

DATA AVAILABILITY

The public release of data supporting the findings of this article will follow the CERN Open Data Policy [56]. The values of relevant plots and tables associated with this article are stored in HEPData [57].

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