EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Phys. Rev. C 111 (2015) 064908
DOI: 10.1103/7lx4-x8rw

CERN-EP-2025-040
23rd June 2025

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

The ATLAS Collaboration

This paper presents the measurement of charged-hadron and identified-hadron (K^0_S, Λ, Ξ^-) yields in photo-nuclear collisions using 1.7 nb^{-1} of $\sqrt{s_{\text{NN}}}$ = 5.02 TeV Pb+Pb data collected in 2018 with the ATLAS detector at the Large Hadron Collider. Candidate photo-nuclear 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 photo-nuclear collisions as a function of charged-particle multiplicity. These photo-nuclear results are compared with 0.1 nb^{-1} of $\sqrt{s_{\text{NN}}}$ = 5.02 TeV p+Pb data collected in 2016 by ATLAS using similar charged-particle multiplicity selections. These photo-nuclear measurements shed light on potential quark-gluon plasma formation in photo-nuclear 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 photo-nuclear collisions may produce small droplets of quark-gluon plasma that flow collectively.

Contents

1 Introduction

When ultra-relativistic 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 “ultra-peripheral 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 photo-nuclear collisions, for example in the case of dijet production [8]. In photo-nuclear reactions, the photon could act as a point-like 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 photo-nuclear (γ+Pb) events by ATLAS [10]. These results indicate significant non-zero 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 photo-nuclear events compared with p+Pb events at the same charged particle multiplicity $N_{\mathrm{ch}}^{\mathrm{rec}}$. The lower elliptic flow in photo-nuclear events may be explained by the stronger longitudinal decorrelations in the rapidity-shifted photo-nuclear events in hydrodynamic calculations [11]. These authors make the specific prediction that the radial flow [13] is essentially the same in photo-nuclear and p+Pb collisions, as measured via the mean transverse momentum, p_{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 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_S^0, Λ, Ξ^-) in photo-nuclear collisions using 1.7 nb^{-1} of $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV Pb+Pb data collected in 2018 with the ATLAS detector at the LHC. The results are compared with measurements in p+Pb collisions specifically to test the predictions of Ref. [11]. Additionally, these photo-nuclear data are compared with the photo-nuclear Monte Carlo (MC) DPMJET-III [18, 19] generator and with hydrodynamic calculations [11] to test the hypothesis of a small QGP droplet formation.

2 The 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

[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.

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.

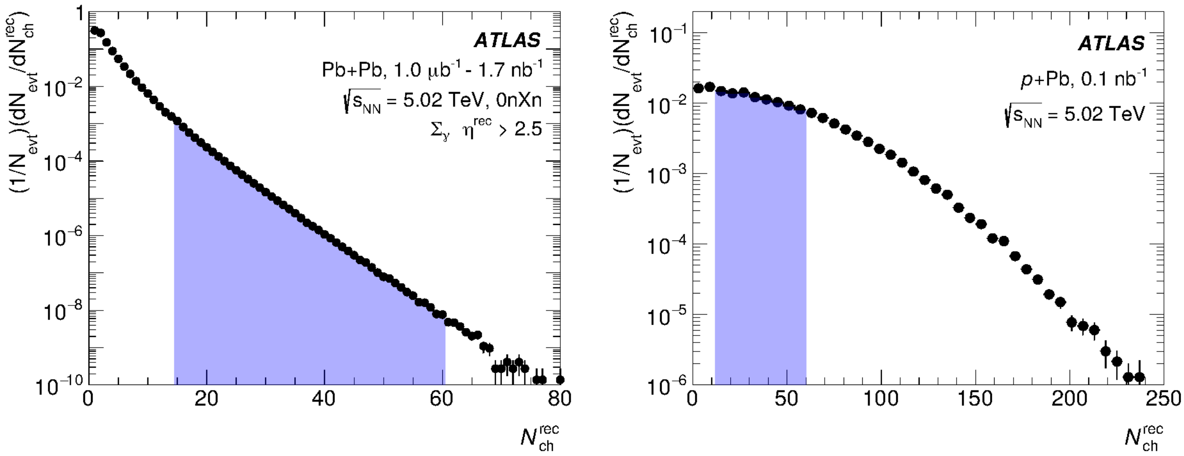
A software suite [24] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Event selection and simulations

Photo-nuclear 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 photo-nuclear 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ 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. Photo-nuclear 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 photo-nuclear collisions, 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) (b)

Figure 1: The multiplicity distributions (N_{ch}^{rec}) from (a) Pb+Pb photo-nuclear and (b) p+Pb collisions. The N_{ch}^{rec} range utilized in this paper, $15 \leq N_{ch}^{rec} \leq 60$, is highlighted.

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 photo-nuclear 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 photo-nuclear Pb+Pb and p+Pb events. The N_{ch}^{rec} range utilized in this paper, $15 \leq N_{ch}^{rec} \leq 60$, is highlighted. The N_{ch}^{rec} differential results are presented in the range $15 \leq N_{ch}^{rec} \leq 60$ and N_{ch}^{rec} integrated results are shown for $25 \leq N_{ch}^{rec} \leq 60$. The p+Pb events are then re-weighted to have effectively the same N_{ch}^{rec} distribution as the UPC Pb+Pb events.

The simulated event sample for the photo-nuclear 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 (γ+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 multi-string 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 multi-particle 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.

4 Analysis

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

4.1 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. In order 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 photo-nuclear 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]:

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

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

4.2 Identified strange hadrons

Only the K_S^0, 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 anti-baryons. Anti-baryons 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 $p_{\mathrm{T}} > 0.1$ GeV and $|\eta| < 2.5$, which are fitted to a common secondary vertex using a Kalman filter [45]. The K_S^0 candidates in the $\pi^+ + \pi^-$ decay mode (branching ratio of 69.2%) are required to satisfy the following criteria:

- The χ^2 of the two-track vertex fit is required to be less than 15 (with one degree of freedom).
- The cosine of the pointing angle in the transverse plane ($\cos\theta$) between the K_S^0 momentum vector and the K_S^0 flight direction, defined as the line connecting the reconstructed primary vertex to the decay direction, is required to fulfill the requirements:
  - $\cos\theta > 0.999$ for Pb+Pb photo-nuclear collisions, except in the most backward rapidity bin, y: $[-2.5, -1.6]$, $\cos\theta > 0.9999$.
  - $\cos\theta > 0.995$ for p+Pb, except in the most backward and forward rapidity bins of p+Pb, y: $[-2.5, -1.6]$ and y: $[1.6, 2.5]$, $\cos\theta > 0.999$
- Requirements on the minimum values of the variables $\left|\frac{L_{\mathrm{xy}}}{\sigma_{L_{\mathrm{xy}}}}\right|$ and $\left|\frac{p_{\mathrm{T}}}{\sigma_{p_{\mathrm{T}}}}\right|$, 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_S^0 candidate) in the transverse plane, $\sigma_{L_{\mathrm{xy}}}$ is the uncertainty on L_{xy} reconstruction, p_{T} is the reconstructed momentum of the K_S^0 candidate and $\sigma_{p_{\mathrm{T}}}$ 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:

- The p_{T} of the Λ candidate is greater than 0.5 GeV.
- The χ^2 of the two-track vertex fit is required to be less than 15 (with one degree of freedom).

- The cosine of the pointing angle ($\cos\theta$) is required to be greater than 0.999.
- Requirements on the minimum values of the variables $\left|\frac{L_{xy}}{\sigma_{L_{xy}}}\right|$ and $\left|\frac{p_T}{\sigma_{p_T}}\right|$, 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:

- The p_T of the Ξ^- candidate is greater than 1 GeV, and $|y| < 1.6$.
- 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).
- The cosine of the pointing angle ($\cos\theta$) associated with Ξ^- vertex is required to be greater than 0.9992.
- The cosine of the pointing angle associated with Λ vertex is required to be greater than 0.99999.
- Requirements on the minimum values of the variables $\left|\frac{L_{xy}}{\sigma_{L_{xy}}}\right|$ 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 $\left|\frac{L_{xy}}{\sigma_{L_{xy}}}\right|$ 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 photo-nuclear collisions. The 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.

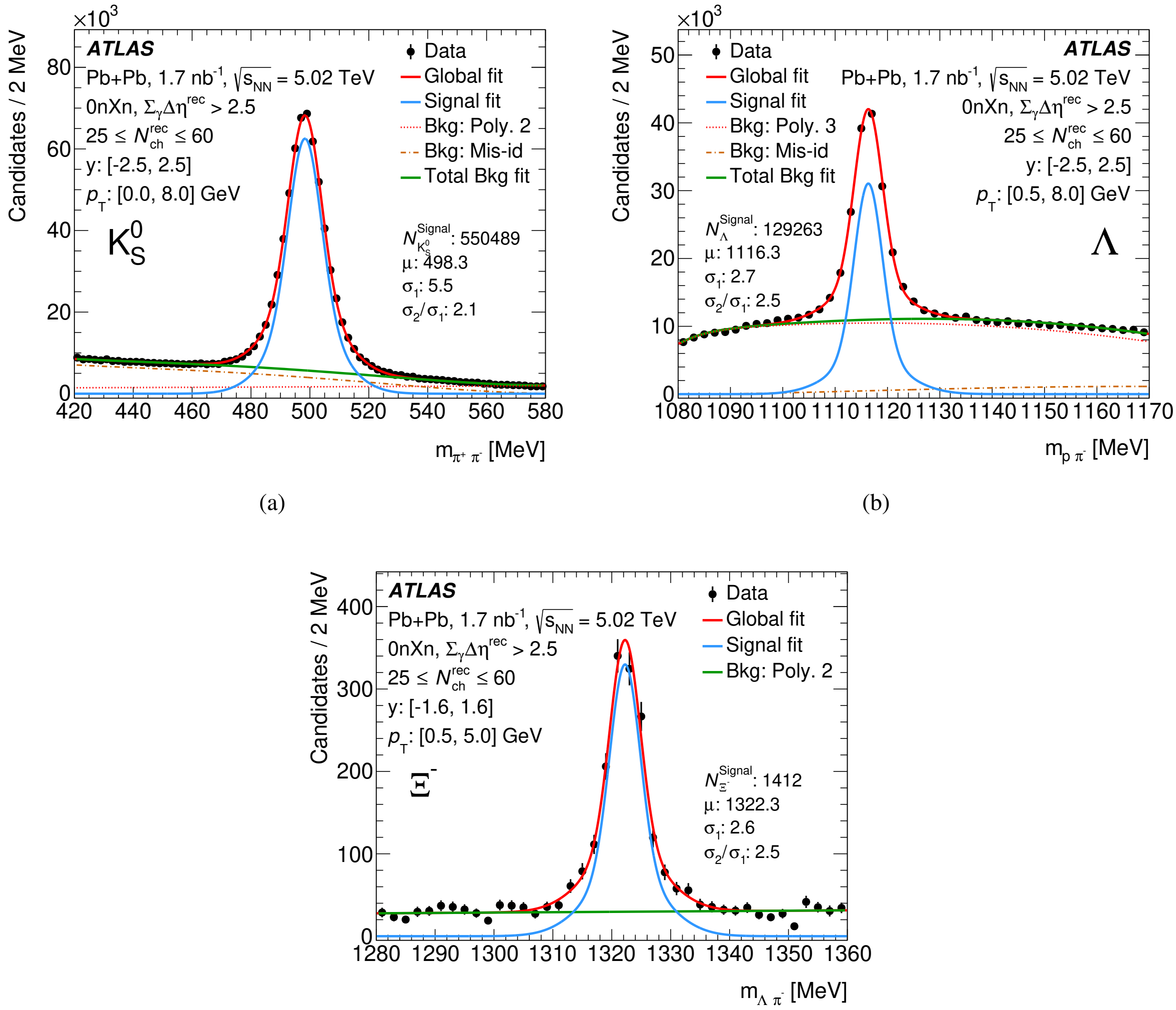
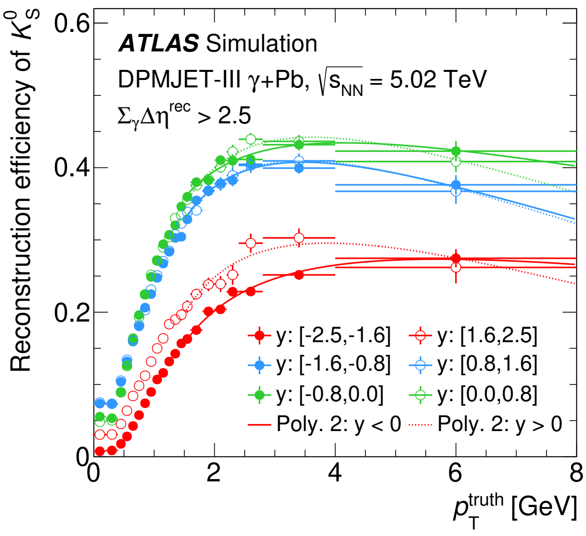
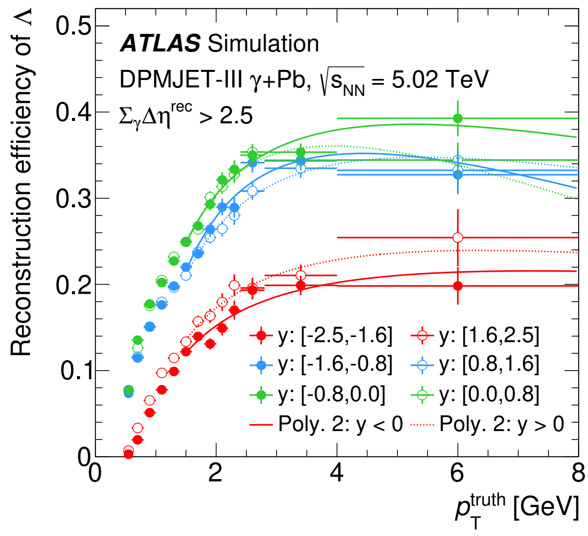


Figure 2: The invariant-mass distributions of (a) K^0_S, (b) Λ, and (c) Ξ^- in Pb+Pb photo-nuclear collisions. The data are fitted to a signal (double Gaussian) and a background component (detailed in the text). The signal counts, and fit parameters for the mean μ and widths σ_1 and σ_2 of the double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

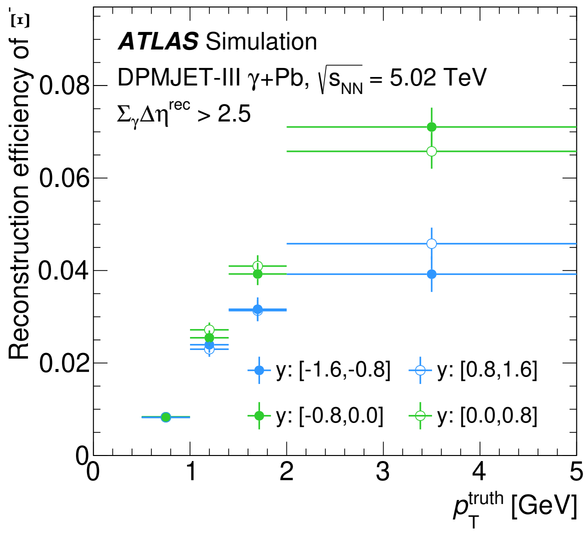
The minimum p_T values are 0 GeV for K^0_S, and 0.5 GeV for Ξ^-. For Λ, the minimum p_T is 0.5 GeV for $|y| < 1.6$ and 0.8 GeV for $1.6 < |y| < 2.5$. Thus the p_T-integrated yields for K^0_S are simply calculated by summing the yields as a function of p_T, whereas for Λ and Ξ^- the yield below the minimum 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 yields in Pb+Pb photo-nuclear 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^0_S 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)



(a)



(b)

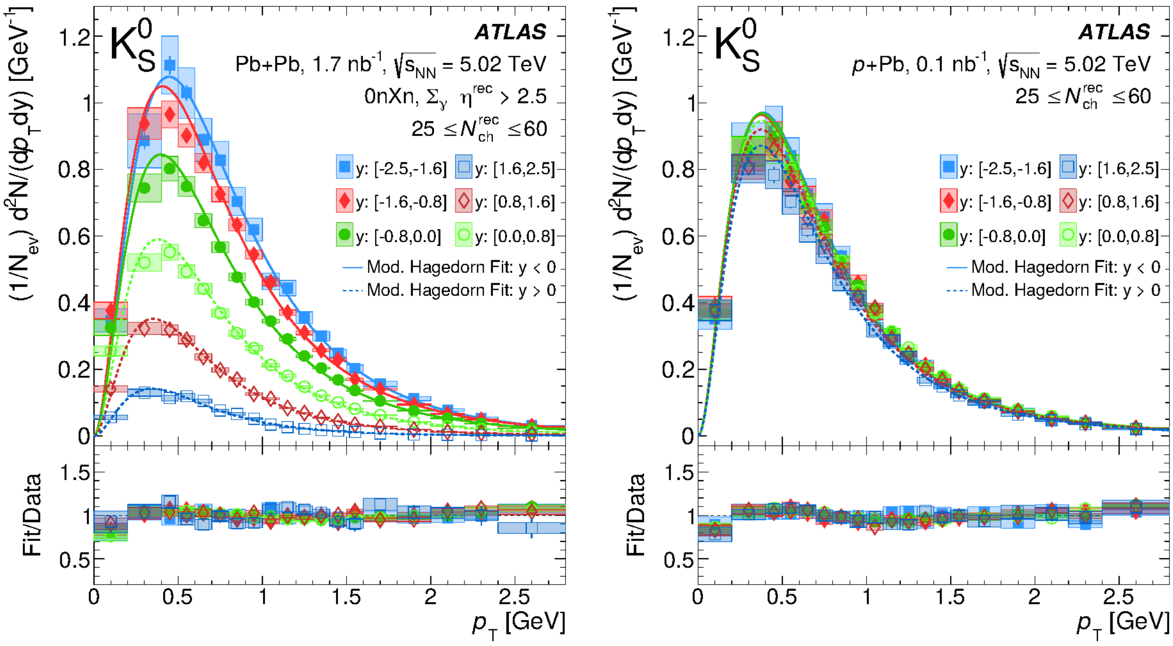


(c)

Figure 3: The 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.

for Ξ^-. Systematic uncertainties on these extrapolations, and from other sources, are discussed below.

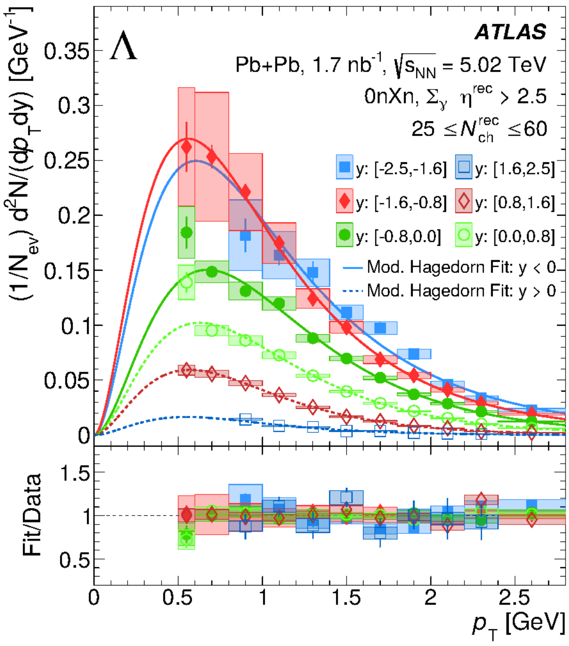
Finally, using the p_T-integrated yields determined above, the $\langle p_T \rangle$ and the ratio of strange-hadron to charged-hadron yields are calculated as a function of N_{ch}^{rec}. These values are calculated after extrapolating down to $p_T = 0$ GeV.



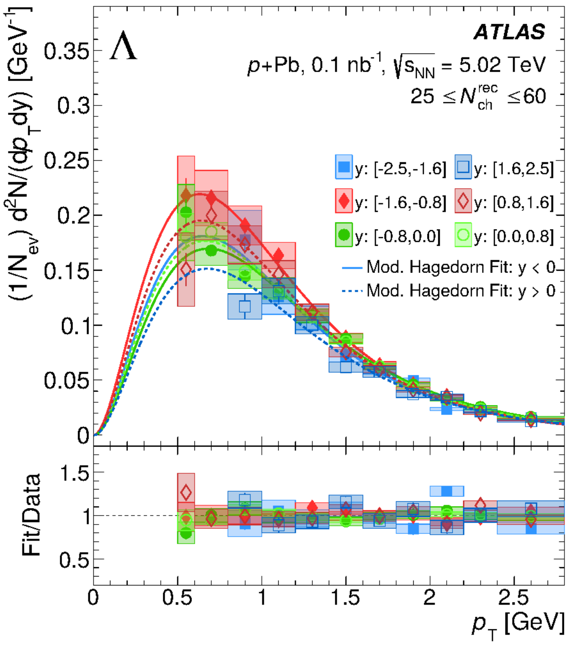
(a)

(b)

Figure 4: The K_S^0 yields as a function of p_T in different y selections in (a) Pb+Pb photo-nuclear 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.



(a)



(b)

Figure 5: The Λ yields as a function of p_T in different y selections in (a) Pb+Pb photo-nuclear 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.

5 Systematic uncertainties

The sources of systematic uncertainties in this measurement are described in the following. For the event selection criteria in Pb+Pb photo-nuclear 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 photo-nuclear and p+Pb collisions, uncertainties are assigned to track selection by relaxing specific hit requirements in turn, 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 re-done 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 photo-nuclear 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.

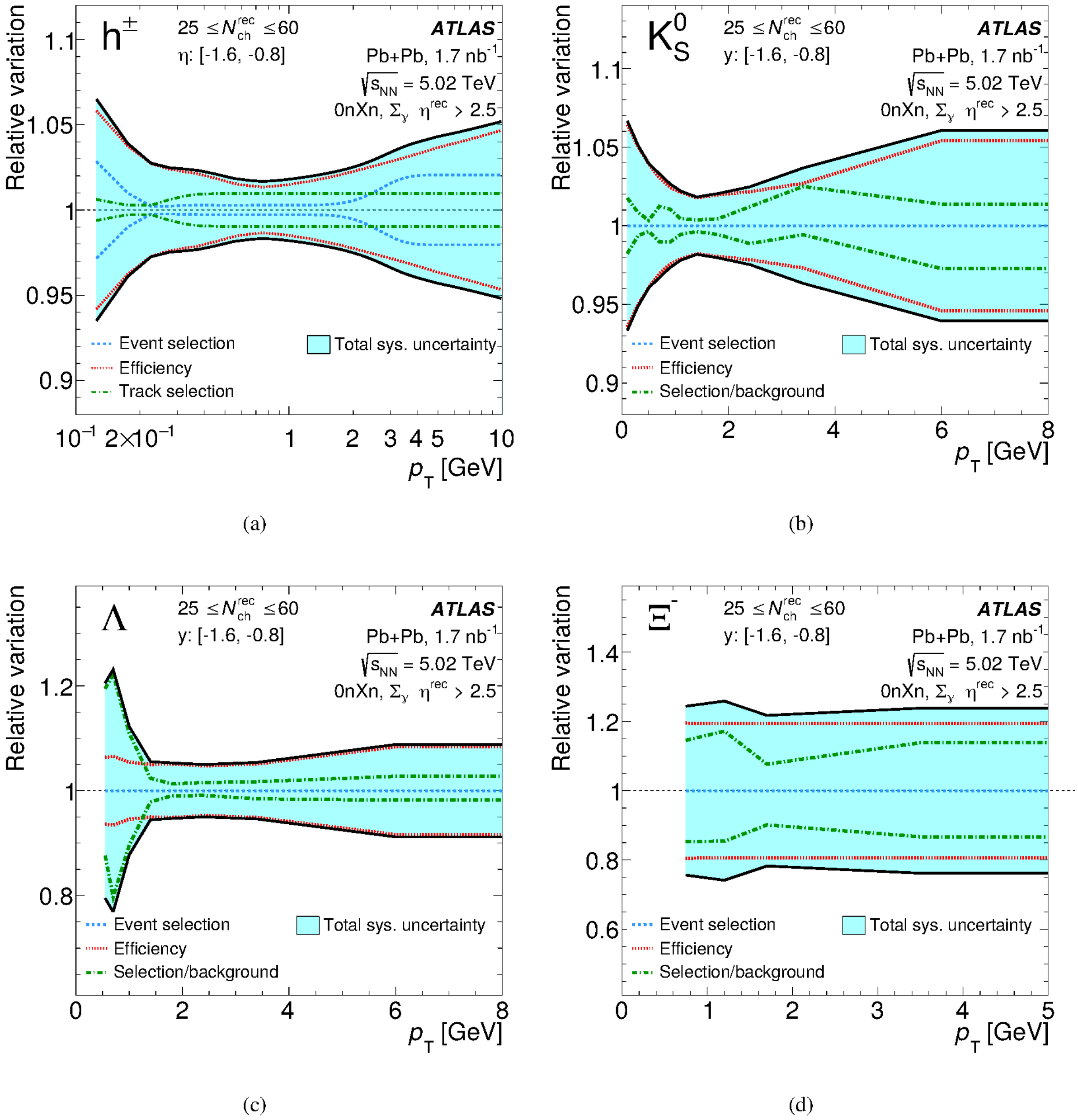


Figure 6: The relative systematic uncertainties in (a) charged hadrons, (b) K^0_S, (c) Λ, and (d) Ξ^- yields in photo-nuclear collisions as a function of p_T. All uncertainty contributions are added in quadrature and the result is symmetrized to obtain the full systematic uncertainty.

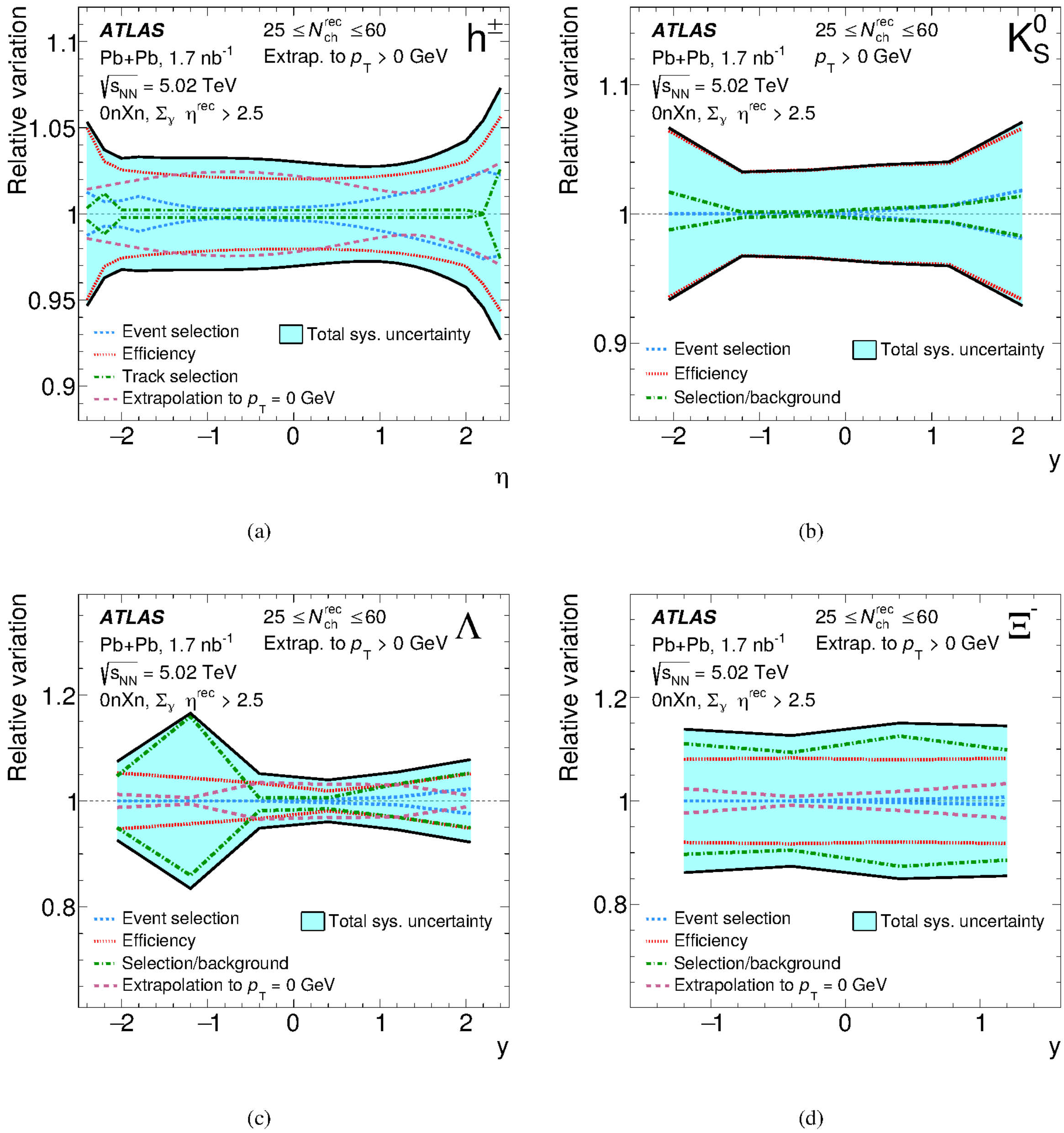


Figure 7: The relative systematic uncertainties in (a) charged hadrons, (b) K^0_S, (c) Λ, and (d) Ξ^- yields in photo-nuclear collisions as a function of (pseudo) rapidity. The yield of K^0_S is measured down to p_T = 0 GeV. For charged hadrons, Λ and Ξ^-, the measured yield is extrapolated to p_T =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

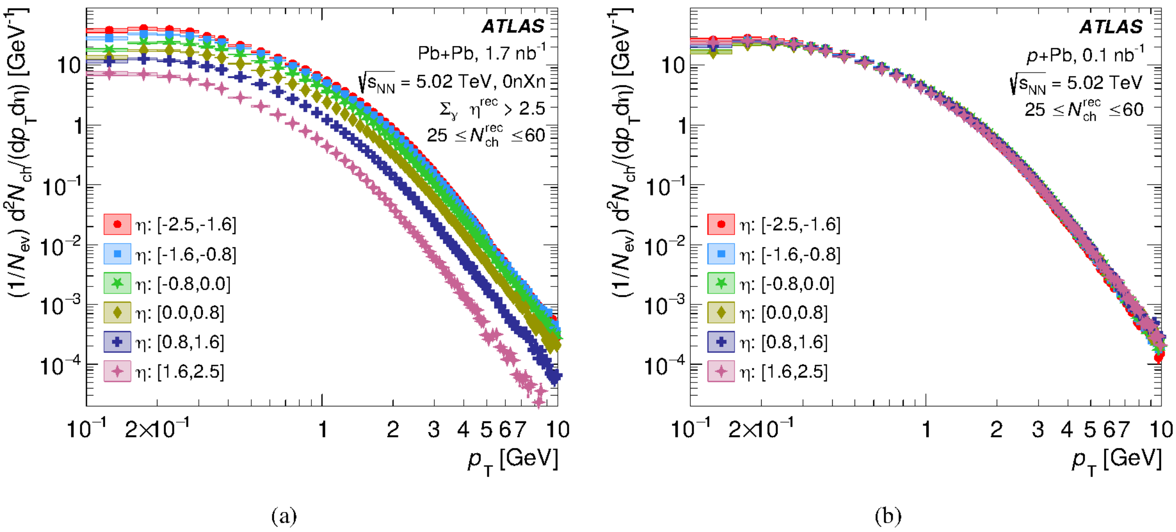
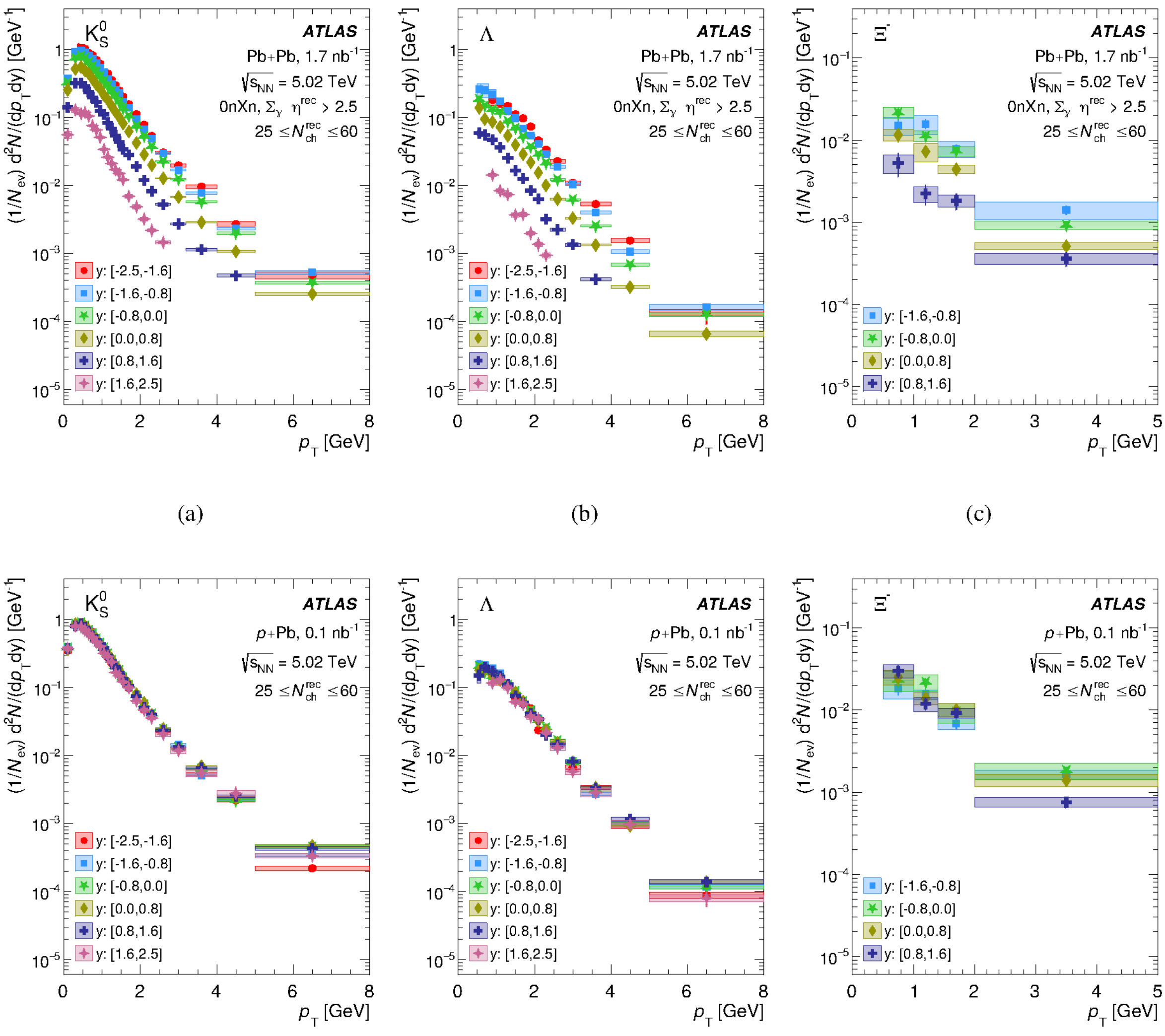


Figure 8: The charged-hadron yields as a function of p_T in six η selections for (a) Pb+Pb photo-nuclear and (b) p+Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

6 Results

The resulting yields as a function of p_T for charged hadrons are shown in Figure 8 in six pseudorapidity selections spanning $-2.5 < \eta < 2.5$ in Pb+Pb photo-nuclear and p+Pb collisions. The yields are calculated for collisions with $25 \leq N_{ch}^{rec} \leq 60$, with the p+Pb N_{ch}^{rec} distribution re-weighted to match that of the photo-nuclear collision sample. The photo-nuclear 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 ($25 \leq N_{ch}^{rec} \leq 60$) are symmetric in rapidity; hence, the η distribution is more pp-like.

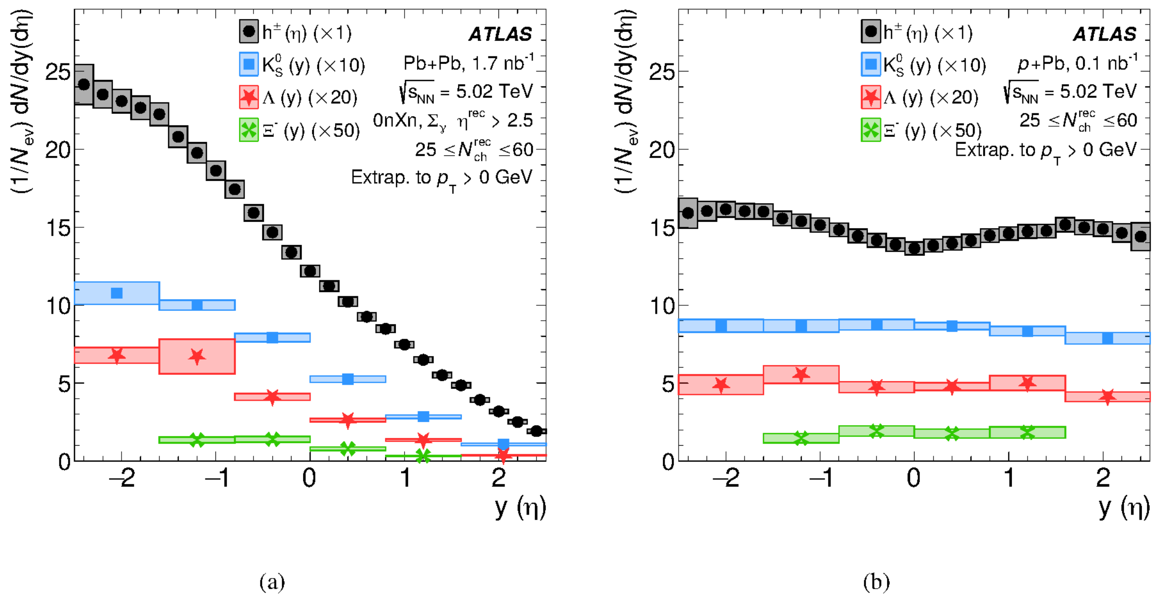
Figure 9 shows the yields as a function of p_T for identified strange hadrons K_S^0, Λ, and Ξ^- in six rapidity selections spanning $-2.5 < y < 2.5$ in Pb+Pb photo-nuclear and p+Pb collisions for the same event selection as the charged-hadron yields. The Λ and Ξ^- yields are for baryons only and are not the average of baryons and anti-baryons. 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 photo-nuclear collisions.



(a) (b) (c)

(d) (e) (f)

Figure 9: The (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 photo-nuclear 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.



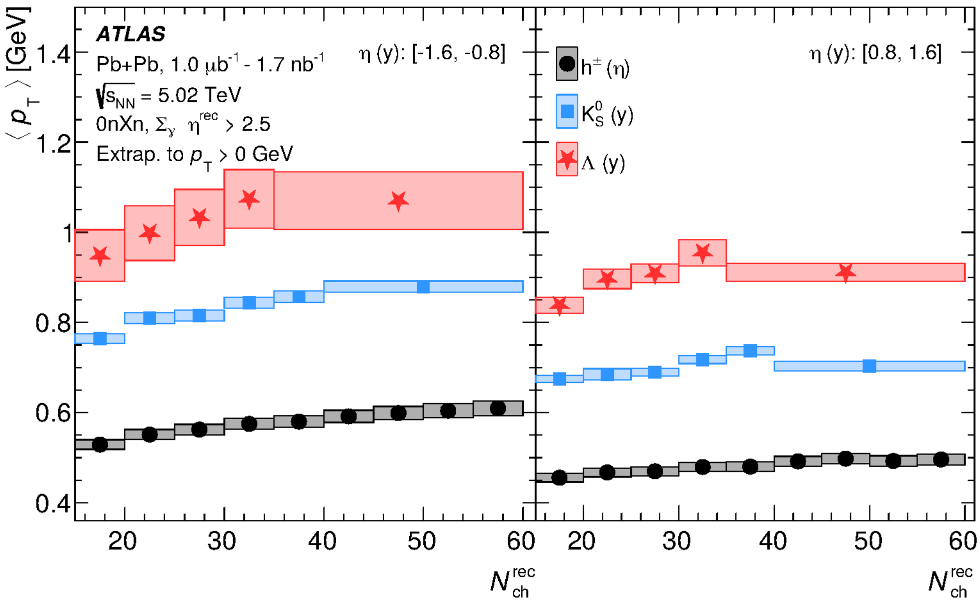
(a) (b)

Figure 10: The 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 photo-nuclear and (b) p+Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

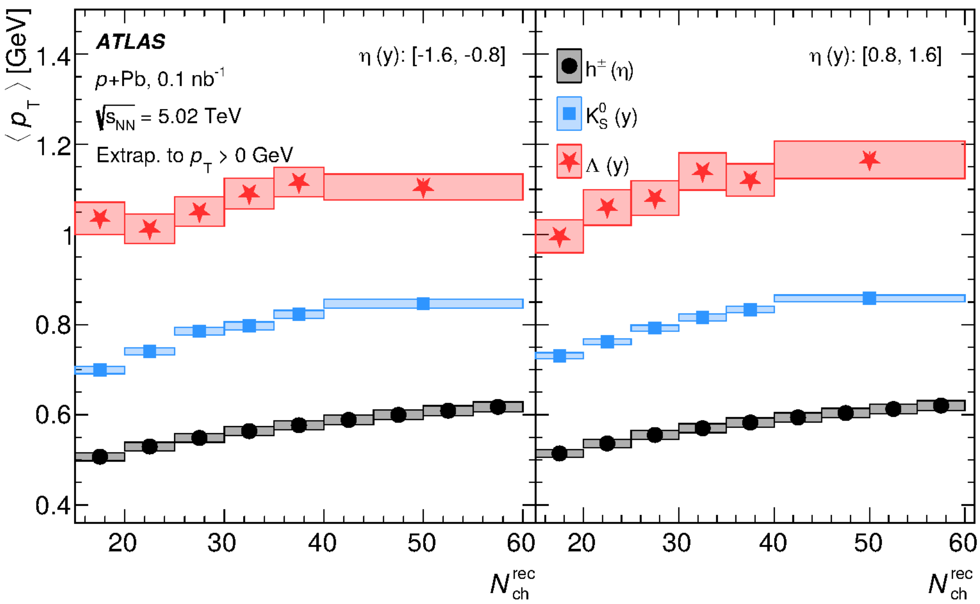
The yields as a function of p_T are then integrated over the p_T range of the measurements, and extrapolated to be inclusive over all p_T, i.e., $p_T > 0$. The resulting p_T-integrated yields as a function of pseudorapidity, for charged hadrons, and rapidity, for identified strange hadrons are shown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

Next, the p_T distributions are characterized in terms of the $\langle p_T \rangle$, calculated to correspond to the mean value for $p_T > 0$. 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 Figure 11. The top (bottom) sub-figures correspond to photo-nuclear Pb+Pb (p+Pb) collisions, with the left (right) panels corresponding to backward (forward) rapidity. In both photo-nuclear 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 photo-nuclear 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.

For the Ξ^-, the $\langle p_T \rangle$ can only be calculated in one selection of N^{rec}_{ch}, $25 \leq N^{rec}_{ch} \leq 60$, 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 photo-nuclear 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+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.

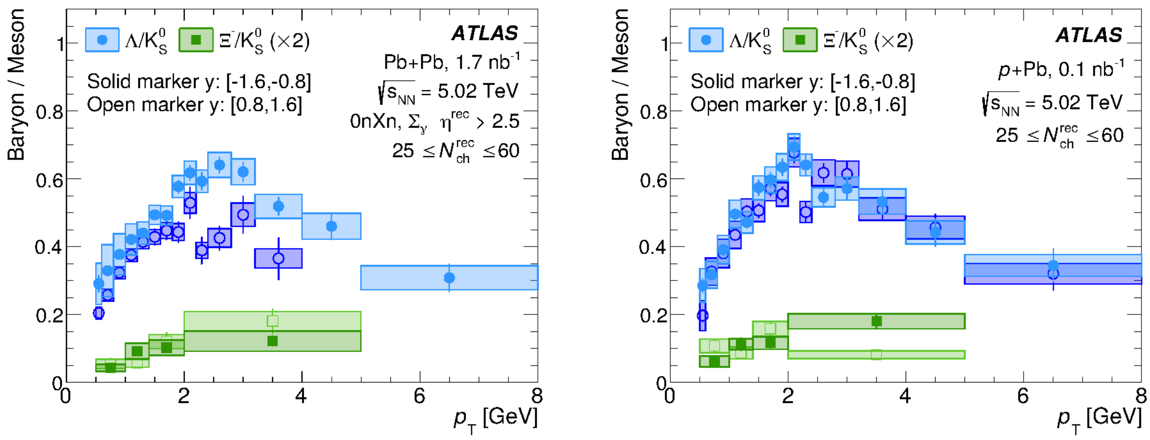


(a)



(b)

Figure 11: The $\langle p_{\mathrm{T}} \rangle$ for charged hadrons, K^0_S, and Λ in (a) Pb+Pb photo-nuclear and (b) p+Pb collisions as a function of $N^{\mathrm{rec}}_{\mathrm{ch}}$. 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.

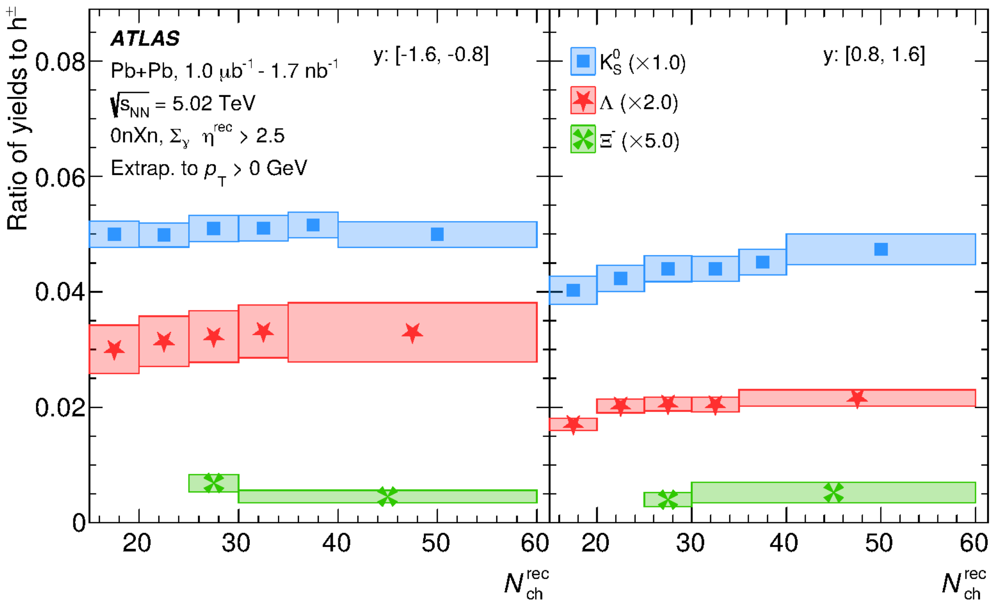


(a) (b)

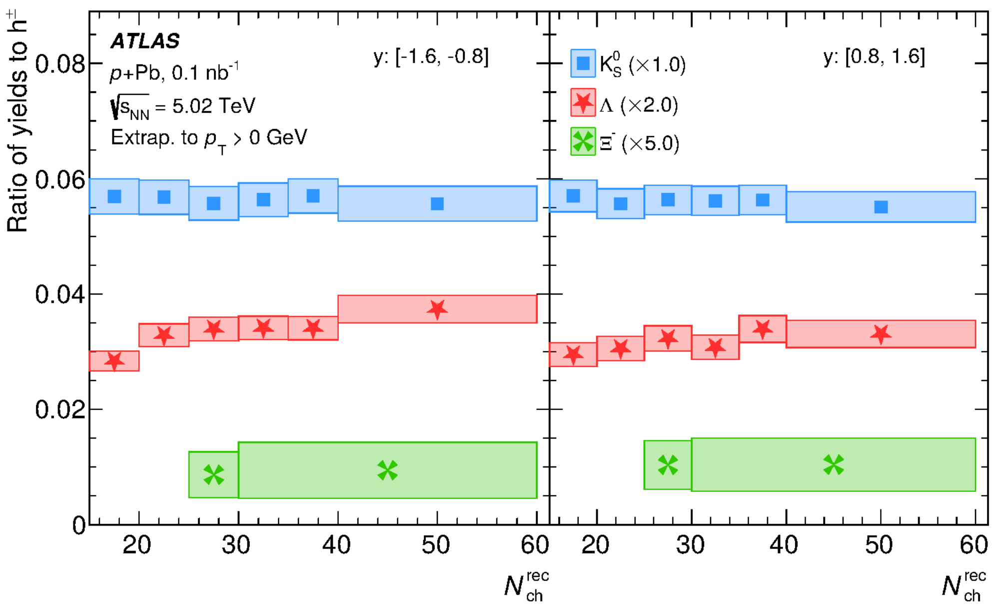
Figure 12: The ratio of Λ/K^0_S and Ξ^-/K^0_S yields as a function of p_T in two rapidity intervals for (a) Pb+Pb photo-nuclear and (b) p+Pb collisions. Statistical uncertainties are shown as vertical lines and systematic uncertainties are shown as colored boxes.

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 photo-nuclear and p+Pb collisions are shown in Figure 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 photo-nuclear collisions. This baryon enhancement at intermediate p_T is reminiscent of the "baryon anomaly" observed in p+Pb and Pb+Pb collisions [51] and is often associated with quark recombination as the dominant hadronization mechanism [52]. The ratios in p+Pb in both rapidity intervals are comparable to the backward rapidity photo-nuclear 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 $N^{\text{rec}}_{\text{ch}}$. The resulting ratios at backward and forward rapidities are shown as a function of $N^{\text{rec}}_{\text{ch}}$ in Figure 13 for photo-nuclear and p+Pb collisions. In photo-nuclear 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 photo-nuclear yields and the p+Pb yields in both rapidity intervals. Overall, the ratios are generally consistent with being flat, i.e., not exhibiting an $N^{\text{rec}}_{\text{ch}}$ 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+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.



(a)



(b)

Figure 13: The ratios of identified-strange-hadron yields to charged-hadron yields as a function of $N_{\mathrm{ch}}^{\mathrm{rec}}$ for (a) Pb+Pb photo-nuclear collisions and (b) p+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.

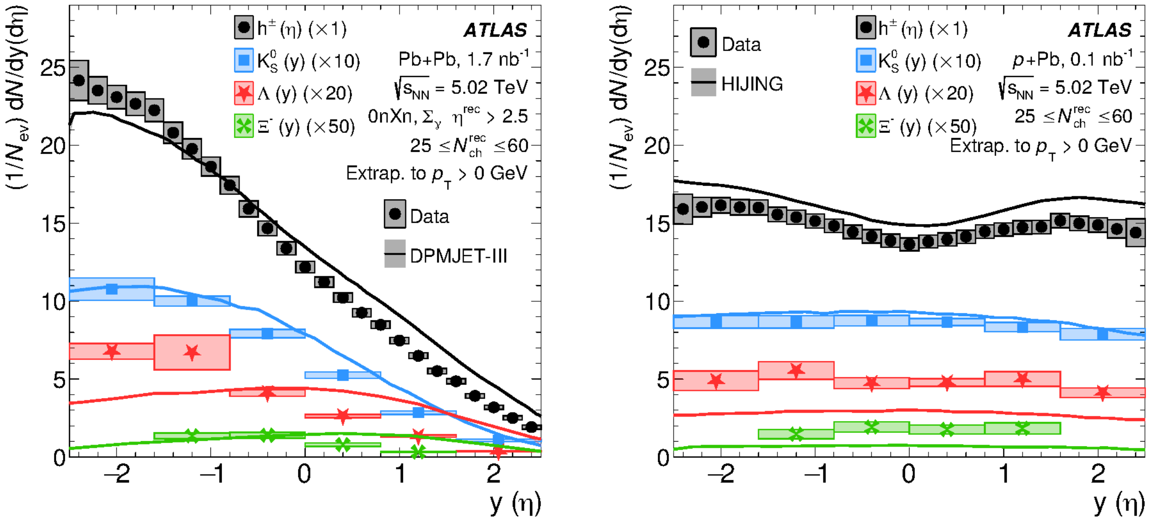
7 Discussion

These experimental results are now compared with DPMJET-III MC for photo-nuclear collisions and HIJING for p+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 photo-nuclear and p+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 photo-nuclear case, following Ref. [9], a parametrization is used for the photon energy and hence the center-of-mass energy distribution. The γ+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+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 $N_{\mathrm{ch}}^{\mathrm{rec}}$ intervals, e.g., $25 \leq N_{\mathrm{ch}}^{\mathrm{rec}} \leq 60$. As discussed earlier, MC studies indicate that the selections on $N_{\mathrm{ch}}^{\mathrm{rec}}$ correspond to equivalent selections on truth-level charged particles with $p_{\mathrm{T}} > 0.4$ GeV and $|\eta| < 2.5$ as well, but with an average value of $N_{\mathrm{ch}}^{\mathrm{truth}} \approx 1.2 \times N_{\mathrm{ch}}^{\mathrm{rec}}$. 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 $p_{\mathrm{T}} > 0.45$ 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 response and reconstruction, i.e., to match the experimental event selection of $N_{\mathrm{ch}}^{\mathrm{rec}}$ and $\sum_{\gamma} \Delta\eta^{\mathrm{rec}}$. 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+Pb measurements at a center-of-mass energy of 5.02 TeV and then made predictions for γ+Pb collisions.

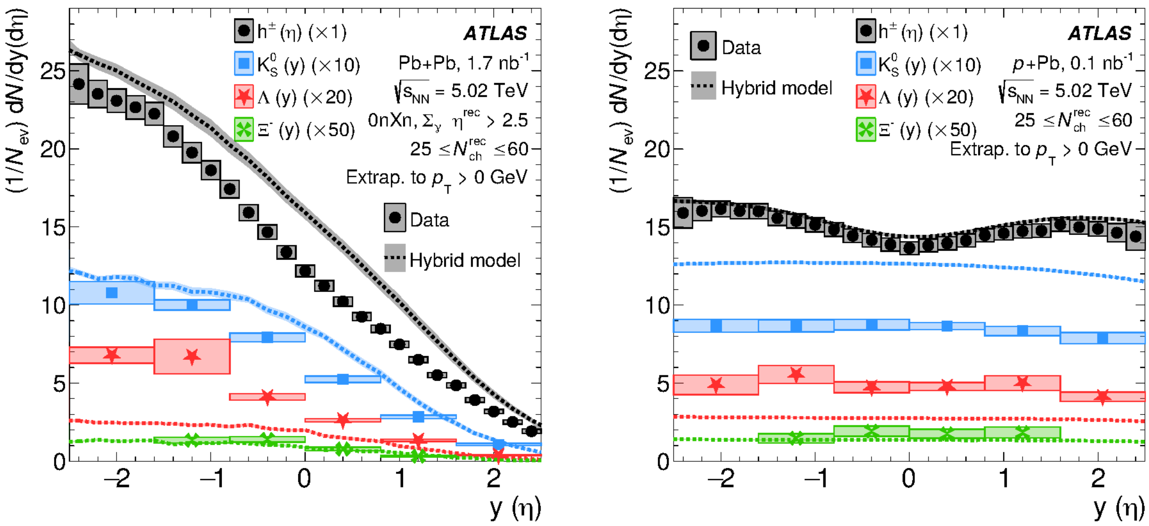
Figure 14 shows the measured charged hadron, K_{S}^0, Λ, and Ξ^- yields as a function of rapidity, compared to MC results from DPMJET-III for photo-nuclear collisions and HIJING for p+Pb collisions. Both calculations describe the charged hadron and K_{S}^0 rapidity dependence and the overall normalization at the 15–25% level. In contrast, the Λ and Ξ^- yields are poorly described with HIJING under-predicting the strange 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 photo-nuclear collisions. For both collision systems, the K_{S}^0 are over-predicted, the Λ under-predicted, and the Ξ^- well described. Since the level of disagreement for strange hadrons (K_{S}^0 and Λ) is similar in both p+Pb and photo-nuclear collisions, it is likely a generic failing of the modeling for strangeness and/or baryons in general in the hadronization of the hydrodynamic QGP.



(a) (b)

Figure 14: The charged-hadron yields as a function of η and the K_S^0, Λ, and Ξ^- yields as a function of y for (a) Pb+Pb photo-nuclear 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.

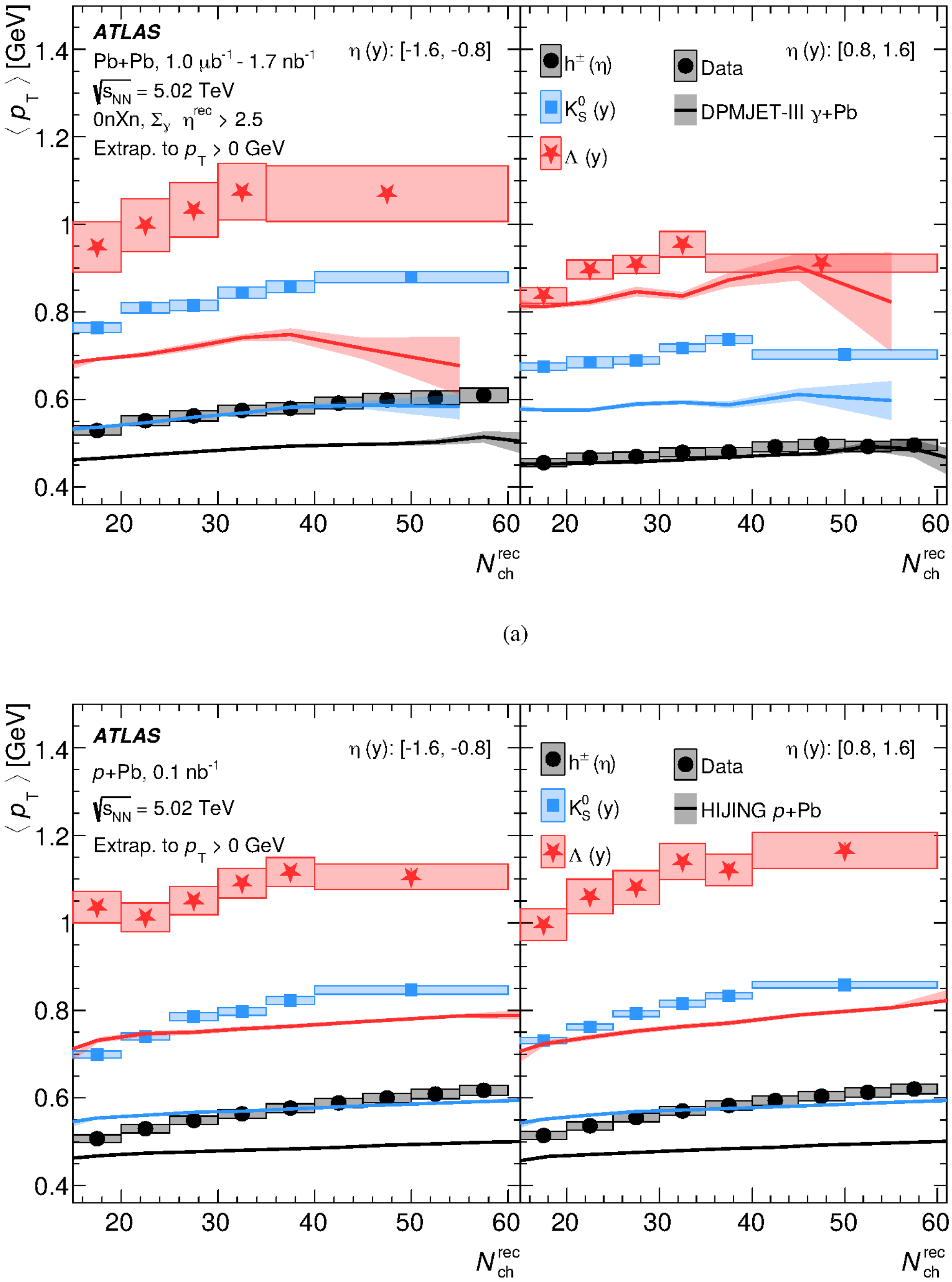


(a) (b)

Figure 15: The charged-hadron yields as a function of η and the K_S^0, Λ, and Ξ^- yields as a function of y for (a) Pb+Pb photo-nuclear 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.

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

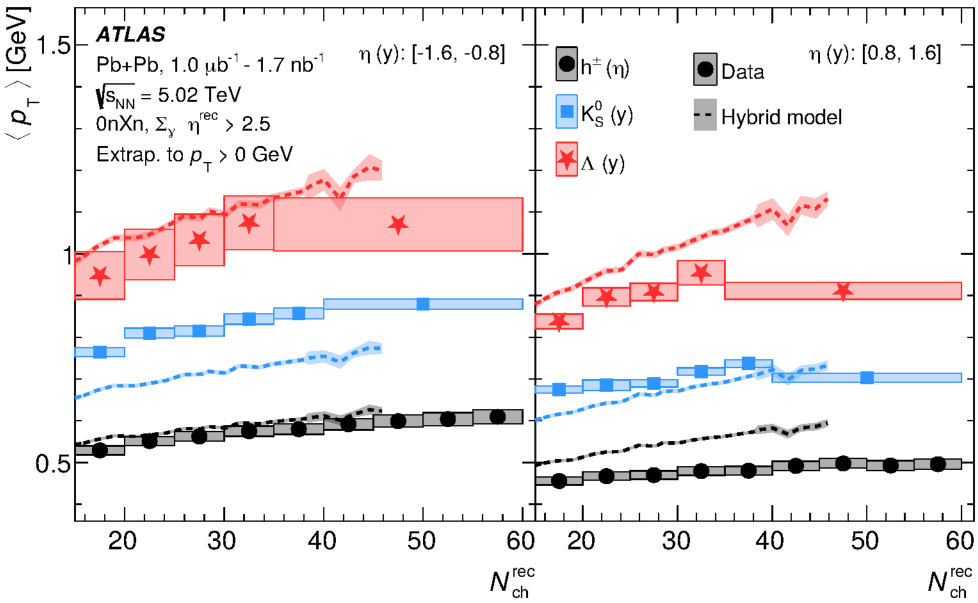
In contrast, the hybrid model provides a reasonable description of the $\langle p_\mathrm{T} \rangle$ of charged hadrons and Λ particles in both photo-nuclear and p+Pb collisions, including the higher $\langle p_\mathrm{T} \rangle$ values at backward rapidity compared to forward rapidity in photo-nuclear collisions. However, the $\langle p_\mathrm{T} \rangle$ values for K_S^0 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 photo-nuclear events remains premature.



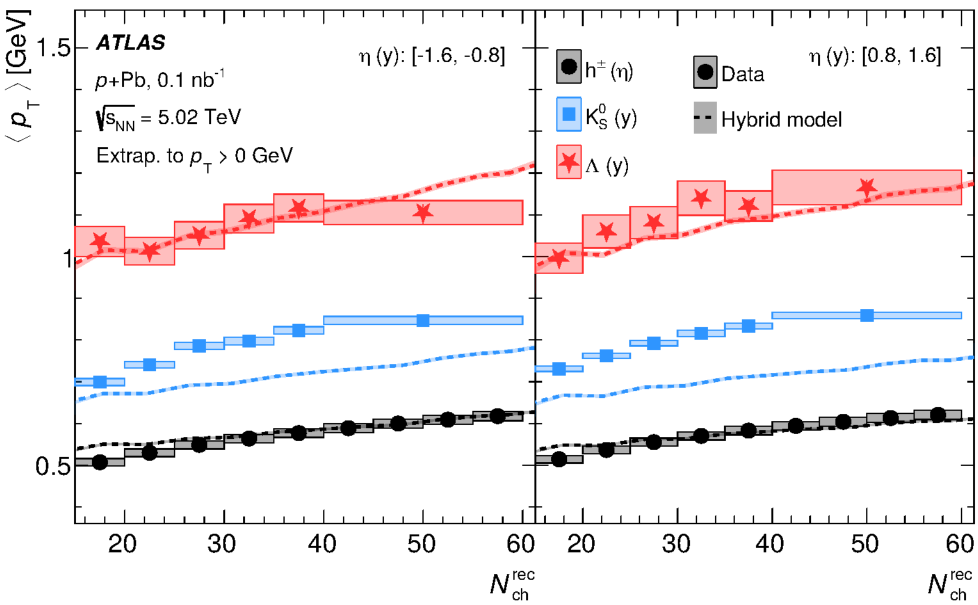
(a)

(b)

Figure 16: The $\langle p_{\mathrm{T}} \rangle$ for charged hadrons, K^0_S, and Λ in (a) Pb+Pb photo-nuclear and (b) p+Pb collisions as a function of $N_{\mathrm{ch}}^{\mathrm{rec}}$. 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 photo-nuclear and p+Pb collisions, respectively, with the shaded bands indicating the statistical uncertainties.



(a)



(b)

Figure 17: The $\langle p_{\mathrm{T}} \rangle$ for charged hadrons, K^0_S, and Λ in (a) Pb+Pb photo-nuclear and (b) p+Pb collisions as a function of $N^{\mathrm{rec}}_{\mathrm{ch}}$. 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.

8 Conclusion

This paper reports a measurement of the yields of charged hadrons and identified K_S^0, Λ, Ξ^- in high-energy photo-nuclear collisions. Events are selected from 1.7 nb^{-1} of $\sqrt{s_{NN}}$ = 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_{ch}^{rec} intervals. The results are compared with p+Pb collision data at comparable N_{ch}^{rec} intervals. These photo-nuclear 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_S^0 (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 photo-nuclear 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 photo-nuclear 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, United States of America.

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 wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN DOCT); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1230987, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265); Czech Republic: Czech Science Foundation (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 (ERC - 101002463); European Union: European Research Council (ERC - 948254, ERC 101089007, 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 (ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - 469666862, 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 (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2020/37/B/ST2/01043, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920, UMO-2024/53/N/ST2/00869); Portugal: Foundation for Science and Technology (FCT); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2021-03651, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR 2024-05451), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2022.0358, KAW 2023.0366); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

References

[1] J. W. Harris and B. Müller, *"QGP Signatures" Revisited*, Eur. Phys. J. C **84** (2024) 247, arXiv: 2308.05743 [hep-ph].

[2] C. A. Bertulani, S. R. Klein and J. Nystrand, *Physics of ultra-peripheral nuclear collisions*, Ann. Rev. Nucl. Part. Sci. **55** (2005) 271, arXiv: nucl-ex/0502005.

[3] S. R. Klein and H. Mäntysaari, *Imaging the nucleus with high-energy photons*, Nature Rev. Phys. **1** (2019) 662, arXiv: 1910.10858 [hep-ex].

[4] ATLAS Collaboration, *Exclusive dimuon production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ATLAS*, Phys. Rev. C **104** (2021) 024906, arXiv: 2011.12211 [nucl-ex].

[5] ATLAS Collaboration, *Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC*, Nature Phys. **13** (2017) 852, arXiv: 1702.01625 [hep-ex].

[6] ATLAS Collaboration, *Observation of Light-by-Light Scattering in Ultraperipheral Pb+Pb Collisions with the ATLAS Detector*, Phys. Rev. Lett. **123** (2019) 052001, arXiv: 1904.03536 [hep-ex].

[7] ATLAS Collaboration, *Observation of the $\gamma\gamma \rightarrow \tau\tau$ Process in Pb+Pb Collisions and Constraints on the τ-Lepton Anomalous Magnetic Moment with the ATLAS Detector*, Phys. Rev. Lett. **131** (2023) 151802, arXiv: 2204.13478 [hep-ex].

[8] ATLAS Collaboration, *Measurement of photonuclear jet production in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector*, (2024), arXiv: 2409.11060 [nucl-ex].

[9] A. J. Baltz et al., *The Physics of Ultraperipheral Collisions at the LHC*, Phys. Rept. **458** (2008) 1, arXiv: 0706.3356 [nucl-ex].

[10] ATLAS Collaboration, *Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS*, Phys. Rev. C **104** (2021) 014903, arXiv: 2101.10771 [nucl-ex].

[11] W. Zhao, C. Shen and B. Schenke, *Collectivity in Ultraperipheral Pb+Pb Collisions at the Large Hadron Collider*, Phys. Rev. Lett. **129** (2022) 252302, arXiv: 2203.06094 [nucl-th].

[12] Y. Shi, L. Wang, S.-Y. Wei, B.-W. Xiao and L. Zheng, *Exploring collective phenomena at the electron-ion collider*, Phys. Rev. D **103** (2021) 054017, arXiv: 2008.03569 [hep-ph].

[13] U. Heinz and R. Snellings, *Collective flow and viscosity in relativistic heavy-ion collisions*, Ann. Rev. Nucl. Part. Sci. **63** (2013) 123, arXiv: 1301.2826 [nucl-th].

[14] R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, *Hadronization in heavy ion collisions: Recombination and fragmentation of partons*, Phys. Rev. Lett. **90** (2003) 202303, arXiv: nucl-th/0301087.

[15] ALICE Collaboration, *Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions*, Nature Phys. **13** (2017) 535, arXiv: 1606.07424 [nucl-ex].

[16] ATLAS Collaboration, *Underlying-event studies with strange hadrons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C **84** (2024) 1335, arXiv: 2405.05048 [hep-ex].

[17] CMS Collaboration, *Two-particle azimuthal correlations in γp interactions using pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV*, Phys. Lett. B **844** (2023) 137905, arXiv: 2204.13486 [nucl-ex].

[18] R. Engel, *Photoproduction within the two-component Dual Parton Model: Amplitudes and cross sections*, Z. Phys. C **66** (1995) 203.

[19] S. Roesler, R. Engel and J. Ranft, 'The Monte Carlo event generator DPMJET-III', *International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications (MC 2000)*, 2000 1033, arXiv: hep-ph/0012252.

[20] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[21] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.

[22] ATLAS Collaboration, *ATLAS Insertable B-Layer: Technical Design Report*, ATLAS-TDR-19; CERN-LHCC-2010-013, 2010, URL: https://cds.cern.ch/record/1291633, Addendum: ATLAS-TDR-19-ADD-1; CERN-LHCC-2012-009, 2012, URL: https://cds.cern.ch/record/1451888.

[23] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, Eur. Phys. J. C **77** (2017) 317, arXiv: 1611.09661 [hep-ex].

[24] ATLAS Collaboration, *Software and computing for Run 3 of the ATLAS experiment at the LHC*, (2024), arXiv: 2404.06335 [hep-ex].

[25] ATLAS Collaboration, *Rapidity gap cross sections measured with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **72** (2012) 1926, arXiv: 1201.2808 [hep-ex].

[26] ATLAS Collaboration, *Correlated long-range mixed-harmonic fluctuations measured in pp, p+Pb and low-multiplicity Pb+Pb collisions with the ATLAS detector*, Phys. Lett. B **789** (2019) 444, arXiv: 1807.02012 [nucl-ex].

[27] ATLAS Collaboration, *Measurement of the Sensitivity of Two-Particle Correlations in pp Collisions to the Presence of Hard Scatterings*, Phys. Rev. Lett. **131** (2023) 162301, arXiv: 2303.17357 [nucl-ex].

[28] ATLAS Collaboration, *Measurement of long-range two-particle azimuthal correlations in Z-boson tagged pp collisions at $\sqrt{s} = 8$ and 13 TeV*, Eur. Phys. J. C **80** (2020) 64, arXiv: 1906.08290 [nucl-ex].

[29] ATLAS Collaboration, *Measurements of long-range azimuthal anisotropies and associated Fourier coefficients for pp collisions at $\sqrt{s} = 5.02$ and 13 TeV and p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector*, Phys. Rev. C **96** (2017) 024908, arXiv: 1609.06213 [nucl-ex].

[30] ATLAS Collaboration, *Measurement of forward-backward multiplicity correlations in lead–lead, proton–lead, and proton–proton collisions with the ATLAS detector*, Phys. Rev. C **95** (2017) 064914, arXiv: 1606.08170 [hep-ex].

[31] S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov and J. Butterworth, *STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions*, Comput. Phys. Commun. **212** (2017) 258, arXiv: 1607.03838 [hep-ph].

[32] C. Y. Wong, *Introduction to High-Energy Heavy-Ion Collisions*, WSPC, 1994, ISBN: 9810202644.

[33] Z. Koba and H. B. Nielsen, *Reaction amplitude for n mesons: A Generalization of the Veneziano-Bardakci-Ruegg-Virasora model*, Nucl. Phys. B **10** (1969) 633.

[34] S. Agostinelli et al., *Geant4 – a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[35] X.-N. Wang and M. Gyulassy, *HIJING: A Monte Carlo model for multiple jet production in pp, pA and AA collisions*, Phys. Rev. D **44** (1991) 3501.

[36] C. Bierlich et al., *A comprehensive guide to the physics and usage of PYTHIA 8.3*, SciPost Phys. Codeb. **2022** (2022) 8, arXiv: 2203.11601 [hep-ph].

[37] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, *Glauber modeling in high energy nuclear collisions*, Ann. Rev. Nucl. Part. Sci. **57** (2007) 205, arXiv: nucl-ex/0701025.

[38] ATLAS Collaboration, *Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC*, New J. Phys. **13** (2011) 053033, arXiv: 1012.5104 [hep-ex].

[39] A. Salzburger, *Optimisation of the ATLAS Track Reconstruction Software for Run-2*, ATL-SOFT-PROC-2015-056, 2015, URL: https://cds.cern.ch/record/2018442.

[40] ATLAS Collaboration, *Charged-particle distributions at low transverse momentum in $\sqrt{s} = 13$ TeV pp interactions measured with the ATLAS detector at the LHC*, Eur. Phys. J. C **76** (2016) 502, arXiv: 1606.01133 [hep-ex].

[41] ATLAS Collaboration, *Modelling of Track Reconstruction Inside Jets with the 2016 ATLAS $\sqrt{s} = 13$ TeV pp Dataset*, ATL-PHYS-PUB-2017-016, 2017, URL: https://cds.cern.ch/record/2275639.

[42] M. Biyajima, T. Mizoguchi, N. Nakajima, N. Suzuki and G. Wilk, *Modified Hagedorn formula including temperature fluctuation: Estimation of temperatures at RHIC experiments*, Eur. Phys. J. C **48** (2006) 597, arXiv: hep-ph/0602120.

[43] ALICE Collaboration, *Strange particle production in proton-proton collisions at sqrt(s) = 0.9 TeV with ALICE at the LHC*, Eur. Phys. J. C **71** (2011) 1594, arXiv: 1012.3257 [hep-ex].

[44] ALICE Collaboration, *Midrapidity antiproton-to-proton ratio in pp collisions at $\sqrt{s} = 0.9$ and 7~TeV measured by the ALICE experiment*, Phys. Rev. Lett. **105** (2010) 072002, arXiv: 1006.5432 [hep-ex].

[45] R. Frühwirth, *Application of Kalman filtering to track and vertex fitting*, Nucl. Instrum. Meth. A **262** (1987) 444.

[46] A. Hoecker et al., *TMVA - Toolkit for Multivariate Data Analysis*, 2009, arXiv: physics/0703039 [physics.data-an].

[47] ATLAS Collaboration, *K_S^0 and Λ production in pp interactions at $\sqrt{s} = 0.9$ and 7 TeV measured with the ATLAS detector at the LHC*, Phys. Rev. D **85** (2012) 012001, arXiv: 1111.1297 [hep-ex].

[48] ATLAS Collaboration, *Charged-particle distributions in* $\sqrt{s} = 13$ *TeV* pp *interactions measured with the ATLAS detector at the LHC*, Phys. Lett. B **758** (2016) 67, arXiv: 1602.01633 [hep-ex].

[49] T. S. Biro and B. Müller, *Almost exponential transverse spectra from power law spectra*, Phys. Lett. B **578** (2004) 78, arXiv: hep-ph/0309052.

[50] ATLAS Collaboration, *Transverse momentum, rapidity, and centrality dependence of inclusive charged-particle production in* $\sqrt{s_{NN}} = 5.02$ *TeV* p+*Pb collisions measured by the ATLAS experiment*, Phys. Lett. B **763** (2016) 313, arXiv: 1605.06436 [hep-ex].

[51] ALICE Collaboration, K^0_S *and* Λ *production in Pb-Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, Phys. Rev. Lett. **111** (2013) 222301, arXiv: 1307.5530 [nucl-ex].

[52] R. J. Fries, V. Greco and P. Sorensen, *Coalescence Models For Hadron Formation From Quark Gluon Plasma*, Ann. Rev. Nucl. Part. Sci. **58** (2008) 177, arXiv: 0807.4939 [nucl-th].

[53] B. Schenke, S. Jeon and C. Gale, *(3+1)D hydrodynamic simulation of relativistic heavy-ion collisions*, Phys. Rev. C **82** (2010) 014903, arXiv: 1004.1408 [hep-ph].

[54] M. Bleicher et al., *Relativistic hadron-hadron collisions in the ultra-relativistic quantum molecular dynamics model*, J. Phys. G **25** (1999) 1859, arXiv: hep-ph/9909407.

[55] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2025-001, 2025, URL: https://cds.cern.ch/record/2922210.

The ATLAS Collaboration

G. Aad [104], E. Aakvaag [17], B. Abbott [123], S. Abdelhameed [119a], K. Abeling [55], N.J. Abicht [49], S.H. Abidi [27b], M. Aboelela [45], A. Aboulhorma [36e], H. Abramowicz [157], Y. Abulaiti [120], B.S. Acharya [69a,69b,n], A. Ackermann [63a], C. Adam Bourdarios [4], L. Adamczyk [86a], S.V. Addepalli [149], M.J. Addison [103], J. Adelman [118], A. Adiguzel [22c], T. Adye [137], A.A. Affolder [139], Y. Afik [40], M.N. Agaras [13], A. Aggarwal [102], C. Agheorghiesei [29c], F. Ahmadov [39,ae], S. Ahuja [97], X. Ai [143b], G. Aielli [76a,76b], A. Aikot [169], M. Ait Tamlihat [36e], B. Aitbenchikh [36a], M. Akbiyik [102], T.P.A. Åkesson [100], A.V. Akimov [151], D. Akiyama [174], N.N. Akolkar [25], S. Aktas [22a], G.L. Alberghi [24b], J. Albert [171], P. Albicocco [53], G.L. Albouy [60], S. Alderweireldt [52], Z.L. Alegria [124], M. Aleksa [37], I.N. Aleksandrov [39], C. Alexa [29b], T. Alexopoulos [10], F. Alfonsi [24b], M. Algren [56], M. Alhroob [173], B. Ali [135], H.M.J. Ali [93,x], S. Ali [32], S.W. Alibocus [94], M. Aliev [34c], G. Alimonti [71a], W. Alkakhi [55], C. Allaire [66], B.M.M. Allbrooke [152], J.S. Allen [103], J.F. Allen [52], P.P. Allport [21], A. Aloisio [72a,72b], F. Alonso [92], C. Alpigiani [142], Z.M.K. Alsolami [93], A. Alvarez Fernandez [102], M. Alves Cardoso [56], M.G. Alviggi [72a,72b], M. Aly [103], Y. Amaral Coutinho [83b], A. Ambler [106], C. Amelung[37], M. Amerl [103], C.G. Ames [111], T. Amezza [130], D. Amidei [108], B. Amini [54], K. Amirie [161], A. Amirkhanov [39], S.P. Amor Dos Santos [133a], K.R. Amos [169], D. Amperiadou [158], S. An[84], C. Anastopoulos [145], T. Andeen [11], J.K. Anders [94], A.C. Anderson [59], A. Andreazza [71a,71b], S. Angelidakis [9], A. Angerami [42], A.V. Anisenkov [39], A. Annovi [74a], C. Antel [56], E. Antipov [151], M. Antonelli [53], F. Anulli [75a], M. Aoki [84], T. Aoki [159], M.A. Aparo [152], L. Aperio Bella [48], M. Apicella[31], C. Appelt [157], A. Apyan [28], S.J. Arbiol Val [87], C. Arcangeletti [53], A.T.H. Arce [51], J-F. Arguin [110], S. Argyropoulos [158], J.-H. Arling [48], O. Arnaez [4], H. Arnold [151], G. Artoni [75a,75b], H. Asada [113], K. Asai [121], S. Asai [159], N.A. Asbah [37], R.A. Ashby Pickering [173], A.M. Aslam [97], K. Assamagan [27b], R. Astalos [30a], K.S.V. Astrand [100], S. Atashi [165], R.J. Atkin [34a], H. Atmani[36f], P.A. Atmasiddha [131], K. Augsten [135], A.D. Auriol [41], V.A. Austrup [103], G. Avolio [37], K. Axiotis [56], G. Azuelos [110,ai], D. Babal [30b], H. Bachacou [138], K. Bachas [158,r], A. Bachiu [35], E. Bachmann [50], M.J. Backes [63a], A. Badea [40], T.M. Baer [108], P. Bagnaia [75a,75b], M. Bahmani [19], D. Bahner [54], K. Bai [126], J.T. Baines [137], L. Baines [96], O.K. Baker [178], E. Bakos [16], D. Bakshi Gupta [8], L.E. Balabram Filho [83b], V. Balakrishnan [123], R. Balasubramanian [4], E.M. Baldin [38], P. Balek [86a], E. Ballabene [24b,24a], F. Balli [138], L.M. Baltes [63a], W.K. Balunas [33], J. Balz [102], I. Bamwidhi [119b], E. Banas [87], M. Bandieramonte [132], A. Bandyopadhyay [25], S. Bansal [25], L. Barak [157], M. Barakat [48], E.L. Barberio [107], D. Barberis [18b], M. Barbero [104], M.Z. Barel [117], T. Barillari [112], M-S. Barisits [37], T. Barklow [149], P. Baron [125], D.A. Baron Moreno [103], A. Baroncelli [62], A.J. Barr [129], J.D. Barr [98], F. Barreiro [101], J. Barreiro Guimarães da Costa [14], M.G. Barros Teixeira [133a], S. Barsov [38], F. Bartels [63a], R. Bartoldus [149], A.E. Barton [93], P. Bartos [30a], A. Basan [102], M. Baselga [49], S. Bashiri[87], A. Bassalat [66,b], M.J. Basso [162a], S. Bataju [45], R. Bate [170], R.L. Bates [59], S. Batlamous[101], M. Battaglia [139], D. Battulga [19], M. Bauce [75a,75b], M. Bauer [79], P. Bauer [25], L.T. Bayer [48], L.T. Bazzano Hurrell [31], J.B. Beacham [112], T. Beau [130], J.Y. Beaucamp [92], P.H. Beauchemin [164], P. Bechtle [25], H.P. Beck [20,q], K. Becker [173], A.J. Beddall [82], V.A. Bednyakov [39], C.P. Bee [151], L.J. Beemster [16], M. Begalli [83d], M. Begel [27b], J.K. Behr [48], J.F. Beirer [37], F. Beisiegel [25], M. Belfkir [119b], G. Bella [157], L. Bellagamba [24b], A. Bellerive [35], C.D. Bellgraph [68], P. Bellos [21], K. Beloborodov [38], D. Benchekroun [36a], F. Bendebba [36a], Y. Benhammou [157], K.C. Benkendorfer [61], L. Beresford [48], M. Beretta [53], E. Bergeaas Kuutmann [167], N. Berger [4],

B. Bergmann[135], J. Beringer[18a], G. Bernardi[5], C. Bernius[149], F.U. Bernlochner[25], F. Bernon[37], A. Berrocal Guardia[13], T. Berry[97], P. Berta[136], A. Berthold[50], A. Berti[133a], R. Bertrand[104], S. Bethke[112], A. Betti[75a,75b], A.J. Bevan[96], L. Bezio[56], N.K. Bhalla[54], S. Bharthuar[112], S. Bhatta[151], P. Bhattarai[149], Z.M. Bhatti[120], K.D. Bhide[54], V.S. Bhopatkar[124], R.M. Bianchi[132], G. Bianco[24b,24a], O. Biebel[111], M. Biglietti[77a], C.S. Billingsley[45], Y. Bimgdi[36f], M. Bindi[55], A. Bingham[177], A. Bingul[22b], C. Bini[75a,75b], G.A. Bird[33], M. Birman[175], M. Biros[136], S. Biryukov[152], T. Bisanz[49], E. Bisceglie[24b,24a], J.P. Biswal[137], D. Biswas[147], I. Bloch[48], A. Blue[59], U. Blumenschein[96], J. Blumenthal[102], V.S. Bobrovnikov[39], M. Boehler[54], B. Boehm[172], D. Bogavac[13], A.G. Bogdanchikov[38], L.S. Boggia[130], V. Boisvert[97], P. Bokan[37], T. Bold[86a], M. Bomben[5], M. Bona[96], M. Boonekamp[138], A.G. Borbély[59], I.S. Bordulev[38], G. Borissov[93], D. Bortoletto[129], D. Boscherini[24b], M. Bosman[13], K. Bouaouda[36a], N. Bouchhar[169], L. Boudet[4], J. Boudreau[132], E.V. Bouhova-Thacker[93], D. Boumediene[41], R. Bouquet[57b,57a], A. Boveia[122], J. Boyd[37], D. Boye[27b], I.R. Boyko[39], L. Bozianu[56], J. Bracinik[21], N. Brahimi[4], G. Brandt[177], O. Brandt[33], B. Brau[105], J.E. Brau[126], R. Brener[175], L. Brenner[117], R. Brenner[167], S. Bressler[175], G. Brianti[78a,78b], D. Britton[59], D. Britzger[112], I. Brock[25], R. Brock[109], G. Brooijmans[42], A.J. Brooks[68], E.M. Brooks[162b], E. Brost[27b], L.M. Brown[171,162a], L.E. Bruce[61], T.L. Bruckler[129], P.A. Bruckman de Renstrom[87], B. Brüers[48], A. Bruni[24b], G. Bruni[24b], D. Brunner[47a,47b], M. Bruschi[24b], N. Bruscino[75a,75b], T. Buanes[17], Q. Buat[142], D. Buchin[112], A.G. Buckley[59], O. Bulekov[82], B.A. Bullard[149], S. Burdin[94], C.D. Burgard[49], A.M. Burger[91], B. Burghgrave[8], O. Burlayenko[54], J. Burleson[168], J.T.P. Burr[33], J.C. Burzynski[148], E.L. Busch[42], V. Büscher[102], P.J. Bussey[59], J.M. Butler[26], C.M. Buttar[59], J.M. Butterworth[98], W. Buttinger[137], C.J. Buxo Vazquez[109], A.R. Buzykaev[39], S. Cabrera Urbán[169], L. Cadamuro[66], D. Caforio[58], H. Cai[132], Y. Cai[24b,114c,24a], Y. Cai[114a], V.M.M. Cairo[37], O. Cakir[3a], N. Calace[37], P. Calafiura[18a], G. Calderini[130], P. Calfayan[35], G. Callea[59], L.P. Caloba[83b], D. Calvet[41], S. Calvet[41], R. Camacho Toro[130], S. Camarda[37], D. Camarero Munoz[28], P. Camarri[76a,76b], C. Camincher[171], M. Campanelli[98], A. Camplani[43], V. Canale[72a,72b], A.C. Canbay[3a], E. Canonero[97], J. Cantero[169], Y. Cao[168], F. Capocasa[28], M. Capua[44b,44a], A. Carbone[71a,71b], R. Cardarelli[76a], J.C.J. Cardenas[8], M.P. Cardiff[28], G. Carducci[44b,44a], T. Carli[37], G. Carlino[72a], J.I. Carlotto[13], B.T. Carlson[132,s], E.M. Carlson[171], J. Carmignani[94], L. Carminati[71a,71b], A. Carnelli[4], M. Carnesale[37], S. Caron[116], E. Carquin[140f], I.B. Carr[107], S. Carrá[71a], G. Carratta[24b,24a], A.M. Carroll[126], M.P. Casado[13,i], M. Caspar[48], F.L. Castillo[4], L. Castillo Garcia[13], V. Castillo Gimenez[169], N.F. Castro[133a,133e], A. Catinaccio[37], J.R. Catmore[128], T. Cavaliere[4], V. Cavaliere[27b], L.J. Caviedes Betancourt[23b], Y.C. Cekmecelioglu[48], E. Celebi[82], S. Cella[37], V. Cepaitis[56], K. Cerny[125], A.S. Cerqueira[83a], A. Cerri[74a,74b,al], L. Cerrito[76a,76b], F. Cerutti[18a], B. Cervato[71a,71b], A. Cervelli[24b], G. Cesarini[53], S.A. Cetin[82], P.M. Chabrillat[130], J. Chan[18a], W.Y. Chan[159], J.D. Chapman[33], E. Chapon[138], B. Chargeishvili[155b], D.G. Charlton[21], C. Chauhan[136], Y. Che[114a], S. Chekanov[6], S.V. Chekulaev[162a], G.A. Chelkov[39,a], B. Chen[157], B. Chen[171], H. Chen[114a], H. Chen[27b], J. Chen[144a], J. Chen[148], M. Chen[129], S. Chen[89], S.J. Chen[114a], X. Chen[144a], X. Chen[15,ah], Z. Chen[62], C.L. Cheng[176], H.C. Cheng[64a], S. Cheong[149], A. Cheplakov[39], E. Cheremushkina[48], E. Cherepanova[117], R. Cherkaoui El Moursli[36e], E. Cheu[7], K. Cheung[65], L. Chevalier[138], V. Chiarella[53], G. Chiarelli[74a], G. Chiodini[70a], A.S. Chisholm[21], A. Chitan[29b], M. Chitishvili[169], M.V. Chizhov[39,t], K. Choi[11], Y. Chou[142], E.Y.S. Chow[116], K.L. Chu[175], M.C. Chu[64a], X. Chu[14,114c], Z. Chubinidze[53], J. Chudoba[134], J.J. Chwastowski[87], D. Cieri[112], K.M. Ciesla[86a], V. Cindro[95], A. Ciocio[18a], F. Cirotto[72a,72b], Z.H. Citron [175], M. Citterio [71a], D.A. Ciubotaru[29b], A. Clark [56], P.J. Clark [52], N. Clarke Hall [98], C. Clarry [161], S.E. Clawson [48], C. Clement [47a,47b], Y. Coadou [104], M. Cobal [69a,69c], A. Coccaro [57b], R.F. Coelho Barrue [133a], R. Coelho Lopes De Sa [105], S. Coelli [71a], L.S. Colangeli [161], B. Cole [42], P. Collado Soto [101], J. Collot [60], R. Coluccia[70a,70b], P. Conde Muiño [133a,133g], M.P. Connell [34c], S.H. Connell [34c], E.I. Conroy [129], F. Conventi [72a,aj], H.G. Cooke [21], A.M. Cooper-Sarkar [129], L. Corazzina [75a,75b], F.A. Corchia [24b,24a], A. Cordeiro Oudot Choi [142], L.D. Corpe [41], M. Corradi [75a,75b], F. Corriveau [106,ac], A. Cortes-Gonzalez [19], M.J. Costa [169], F. Costanza [4], D. Costanzo [145], B.M. Cote [122], J. Couthures [4], G. Cowan [97], K. Cranmer [176], L. Cremer [49], D. Cremonini [24b,24a], S. Crépé-Renaudin [60], F. Crescioli [130], T. Cresta [73a,73b], M. Cristinziani [147], M. Cristoforetti [78a,78b], V. Croft [117], J.E. Crosby [124], G. Crosetti [44b,44a], A. Cueto [101], H. Cui [98], Z. Cui [7], W.R. Cunningham [59], F. Curcio [169], J.R. Curran [52], M.J. Da Cunha Sargedas De Sousa [57b,57a], J.V. Da Fonseca Pinto [83b], C. Da Via [103], W. Dabrowski [86a], T. Dado [37], S. Dahbi [154], T. Dai [108], D. Dal Santo [20], C. Dallapiccola [105], M. Dam [43], G. D'amen [27b], V. D'Amico [111], J. Damp [102], J.R. Dandoy [35], D. Dannheim [37], G. D'anniballe [74a,74b], M. Danninger [148], V. Dao [151], G. Darbo [57b], S.J. Das [27b], F. Dattola [48], S. D'Auria [71a,71b], A. D'Avanzo [72a,72b], T. Davidek [136], J. Davidson [173], I. Dawson [96], K. De [8], C. De Almeida Rossi [161], R. De Asmundis [72a], N. De Biase [48], S. De Castro [24b,24a], N. De Groot [116], P. de Jong [117], H. De la Torre [118], A. De Maria [114a], A. De Salvo [75a], U. De Sanctis [76a,76b], F. De Santis [70a,70b], A. De Santo [152], J.B. De Vivie De Regie [60], J. Debevc [95], D.V. Dedovich[39], J. Degens [94], A.M. Deiana [45], J. Del Peso [101], L. Delagrange [130], F. Deliot [138], C.M. Delitzsch [49], M. Della Pietra [72a,72b], D. Della Volpe [56], A. Dell'Acqua [37], L. Dell'Asta [71a,71b], M. Delmastro [4], C.C. Delogu [102], P.A. Delsart [60], S. Demers [178], M. Demichev [39], S.P. Denisov [38], H. Denizli [22a,m], L. D'Eramo [41], D. Derendarz [87], F. Derue [130], P. Dervan [94], K. Desch [25], F.A. Di Bello [57b,57a], A. Di Ciaccio [76a,76b], L. Di Ciaccio [4], A. Di Domenico [75a,75b], C. Di Donato [72a,72b], A. Di Girolamo [37], G. Di Gregorio [37], A. Di Luca [78a,78b], B. Di Micco [77a,77b], R. Di Nardo [77a,77b], K.F. Di Petrillo [40], M. Diamantopoulou [35], F.A. Dias [117], M.A. Diaz [140a,140b], A.R. Didenko [39], M. Didenko [169], S.D. Diefenbacher [18a], E.B. Diehl [108], S. Díez Cornell [48], C. Diez Pardos [147], C. Dimitriadi [150], A. Dimitrievska [21], A. Dimri [151], J. Dingfelder [25], T. Dingley [129], I-M. Dinu [29b], S.J. Dittmeier [63b], F. Dittus [37], M. Divisek [136], B. Dixit [94], F. Djama [104], T. Djobava [155b], C. Doglioni [103,100], A. Dohnalova [30a], Z. Dolezal [136], K. Domijan [86a], K.M. Dona [40], M. Donadelli [83d], B. Dong [109], J. Donini [41], A. D'Onofrio [72a,72b], M. D'Onofrio [94], J. Dopke [137], A. Doria [72a], N. Dos Santos Fernandes [133a], P. Dougan [103], M.T. Dova [92], A.T. Doyle [59], M.A. Draguet [129], M.P. Drescher [55], E. Dreyer [175], I. Drivas-koulouris [10], M. Drnevich [120], M. Drozdova [56], D. Du [62], T.A. du Pree [117], Z. Duan[114a], F. Dubinin [39], M. Dubovsky [30a], E. Duchovni [175], G. Duckeck [111], P.K. Duckett[98], O.A. Ducu [29b], D. Duda [52], A. Dudarev [37], E.R. Duden [28], M. D'uffizi [103], L. Duflot [66], M. Dührssen [37], I. Duminica [29g], A.E. Dumitriu [29b], M. Dunford [63a], S. Dungs [49], K. Dunne [47a,47b], A. Duperrin [104], H. Duran Yildiz [3a], M. Düren [58], A. Durglishvili [155b], D. Duvnjak [35], B.L. Dwyer [118], G.I. Dyckes [18a], M. Dyndal [86a], B.S. Dziedzic [37], Z.O. Earnshaw [152], G.H. Eberwein [129], B. Eckerova [30a], S. Eggebrecht [55], E. Egidio Purcino De Souza [83e], G. Eigen [17], K. Einsweiler [18a], T. Ekelof [167], P.A. Ekman [100], S. El Farkh [36b], Y. El Ghazali [62], H. El Jarrari [37], A. El Moussaouy [36a], V. Ellajosyula [167], M. Ellert [167], F. Ellinghaus [177], N. Ellis [37], J. Elmsheuser [27b], M. Elsawy [119a], M. Elsing [37], D. Emeliyanov [137], Y. Enari [84], I. Ene [18a], S. Epari [110], D. Ernani Martins Neto [87], F. Ernst[37], M. Errenst [177], M. Escalier [66], C. Escobar [169], E. Etzion [157], G. Evans [133a,133b], H. Evans [68], L.S. Evans [97], A. Ezhilov [38], S. Ezzarqtouni [36a],

F. Fabbri [24b,24a], L. Fabbri [24b,24a], G. Facini [98], V. Fadeyev [139], R.M. Fakhrutdinov [38], D. Fakoudis [102], S. Falciano [75a], L.F. Falda Ulhoa Coelho [133a], F. Fallavollita [112], G. Falsetti [44b,44a], J. Faltova [136], C. Fan [168], K.Y. Fan [64b], Y. Fan [14], Y. Fang [14,114c], M. Fanti [71a,71b], M. Faraj [69a,69b], Z. Farazpay [99], A. Farbin [8], A. Farilla [77a], T. Farooque [109], J.N. Farr [178], S.M. Farrington [137,52], F. Fassi [36e], D. Fassouliotis [9], L. Fayard [66], P. Federic [136], P. Federicova [134], O.L. Fedin [38,a], M. Feickert [176], L. Feligioni [104], D.E. Fellers [18a], C. Feng [143a], Z. Feng [117], M.J. Fenton [165], L. Ferencz [48], B. Fernandez Barbadillo [93], P. Fernandez Martinez [67], M.J.V. Fernoux [104], J. Ferrando [93], A. Ferrari [167], P. Ferrari [117,116], R. Ferrari [73a], D. Ferrere [56], C. Ferretti [108], M.P. Fewell [1], D. Fiacco [75a,75b], F. Fiedler [102], P. Fiedler [135], S. Filimonov [39], M.S. Filip [29b,u], A. Filipčič [95], E.K. Filmer [162a], F. Filthaut [116], M.C.N. Fiolhais [133a,133c,c], L. Fiorini [169], W.C. Fisher [109], T. Fitschen [103], P.M. Fitzhugh [138], I. Fleck [147], P. Fleischmann [108], T. Flick [177], M. Flores [34d,ag], L.R. Flores Castillo [64a], L. Flores Sanz De Acedo [37], F.M. Follega [78a,78b], N. Fomin [33], J.H. Foo [161], A. Formica [138], A.C. Forti [103], E. Fortin [37], A.W. Fortman [18a], L. Foster [18a], L. Fountas [9,j], D. Fournier [66], H. Fox [93], P. Francavilla [74a,74b], S. Francescato [61], S. Franchellucci [56], M. Franchini [24b,24a], S. Franchino [63a], D. Francis [37], L. Franco [116], V. Franco Lima [37], L. Franconi [48], M. Franklin [61], G. Frattari [28], Y.Y. Frid [157], J. Friend [59], N. Fritzsche [37], A. Froch [56], D. Froidevaux [37], J.A. Frost [129], Y. Fu [109], S. Fuenzalida Garrido [140f], M. Fujimoto [104], K.Y. Fung [64a], E. Furtado De Simas Filho [83e], M. Furukawa [159], J. Fuster [169], A. Gaa [55], A. Gabrielli [24b,24a], A. Gabrielli [161], P. Gadow [37], G. Gagliardi [57b,57a], L.G. Gagnon [18a], S. Gaid [88b], S. Galantzan [157], J. Gallagher [1], E.J. Gallas [129], A.L. Gallen [167], B.J. Gallop [137], K.K. Gan [122], S. Ganguly [159], Y. Gao [52], A. Garabaglu [142], F.M. Garay Walls [140a,140b], C. García [169], A. Garcia Alonso [117], A.G. Garcia Caffaro [178], J.E. García Navarro [169], M. Garcia-Sciveres [18a], G.L. Gardner [131], R.W. Gardner [40], N. Garelli [164], R.B. Garg [149], J.M. Gargan [52], C.A. Garner [161], C.M. Garvey [34a], V.K. Gassmann [164], G. Gaudio [73a], V. Gautam [13], P. Gauzzi [75a,75b], J. Gavranovic [95], I.L. Gavrilenko [133a], A. Gavrilyuk [38], C. Gay [170], G. Gaycken [126], E.N. Gazis [10], A. Gekow [122], C. Gemme [57b], M.H. Genest [60], A.D. Gentry [115], S. George [97], T. Geralis [46], A.A. Gerwin [123], P. Gessinger-Befurt [37], M.E. Geyik [177], M. Ghani [173], K. Ghorbanian [96], A. Ghosal [147], A. Ghosh [165], A. Ghosh [7], B. Giacobbe [24b], S. Giagu [75a,75b], T. Giani [117], A. Giannini [62], S.M. Gibson [97], M. Gignac [139], D.T. Gil [86b], A.K. Gilbert [86a], B.J. Gilbert [42], D. Gillberg [35], G. Gilles [117], D.M. Gingrich [2,ai], M.P. Giordani [69a,69c], P.F. Giraud [138], G. Giugliarelli [69a,69c], D. Giugni [71a], F. Giuli [76a,76b], I. Gkialas [9,j], L.K. Gladilin [38], C. Glasman [101], M. Glazewska [20], G. Glemža [48], M. Glisic [126], I. Gnesi [44b], Y. Go [27b], M. Goblirsch-Kolb [37], B. Gocke [49], D. Godin [110], B. Gokturk [22a], S. Goldfarb [107], T. Golling [56], M.G.D. Gololo [34c], D. Golubkov [38], J.P. Gombas [109], A. Gomes [133a,133b], G. Gomes Da Silva [147], A.J. Gomez Delegido [169], R. Gonçalo [133a], L. Gonella [21], A. Gongadze [155c], F. Gonnella [21], J.L. Gonski [149], R.Y. González Andana [52], S. González de la Hoz [169], M.V. Gonzalez Rodrigues [48], R. Gonzalez Suarez [167], S. Gonzalez-Sevilla [56], L. Goossens [37], B. Gorini [37], E. Gorini [70a,70b], A. Gorišek [95], T.C. Gosart [131], A.T. Goshaw [51], M.I. Gostkin [39], S. Goswami [124], C.A. Gottardo [37], S.A. Gotz [111], M. Gouighri [36b], A.G. Goussiou [142], N. Govender [34c], R.P. Grabarczyk [129], I. Grabowska-Bold [86a], K. Graham [35], E. Gramstad [128], S. Grancagnolo [70a,70b], C.M. Grant [1], P.M. Gravila [29f], F.G. Gravili [70a,70b], H.M. Gray [18a], M. Greco [112], M.J. Green [1], C. Grefe [25], A.S. Grefsrud [17], I.M. Gregor [48], K.T. Greif [165], P. Grenier [149], S.G. Grewe [112], A.A. Grillo [139], K. Grimm [32], S. Grinstein [13,y], J.-F. Grivaz [66], E. Gross [175], J. Grosse-Knetter [55], L. Guan [108], G. Guerrieri [37], R. Guevara [128], R. Gugel [102], J.A.M. Guhit [108], A. Guida [19], E. Guilloton [173], S. Guindon [37], F. Guo [14,114c], J. Guo [144a], L. Guo [48], L. Guo [114b,w], Y. Guo [108], A. Gupta [49],

R. Gupta [132], S. Gupta [28], S. Gurbuz [25], S.S. Gurdasani [48], G. Gustavino [75a,75b], P. Gutierrez [123], L.F. Gutierrez Zagazeta [131], M. Gutsche [50], C. Gutschow [98], C. Gwenlan [129], C.B. Gwilliam [94], E.S. Haaland [128], A. Haas [120], M. Habedank [59], C. Haber [18a], H.K. Hadavand [8], A. Haddad [41], A. Hadef [50], A.I. Hagan [93], J.J. Hahn [147], E.H. Haines [98], M. Haleem [172], J. Haley [124], G.D. Hallewell [104], L. Halser [20], K. Hamano [171], M. Hamer [25], S.E.D. Hammoud [66], E.J. Hampshire [97], J. Han [143a], L. Han [114a], L. Han [62], S. Han [18a], K. Hanagaki [84], M. Hance [139], D.A. Hangal [42], H. Hanif [148], M.D. Hank [131], J.B. Hansen [43], P.H. Hansen [43], D. Harada [56], T. Harenberg [177], S. Harkusha [179], M.L. Harris [105], Y.T. Harris [25], J. Harrison [13], N.M. Harrison [122], P.F. Harrison[173], M.L.E. Hart [98], N.M. Hartman [112], N.M. Hartmann [111], R.Z. Hasan [97,137], Y. Hasegawa [146], F. Haslbeck [129], S. Hassan [17], R. Hauser [109], M. Haviernik [136], C.M. Hawkes [21], R.J. Hawkings [37], Y. Hayashi [159], D. Hayden [109], C. Hayes [108], R.L. Hayes [117], C.P. Hays [129], J.M. Hays [96], H.S. Hayward [94], M. He [14,114c], Y. He [48], Y. He [98], N.B. Heatley [96], V. Hedberg [100], C. Heidegger [54], K.K. Heidegger [54], J. Heilman [35], S. Heim [48], T. Heim [18a], J.G. Heinlein [131], J.J. Heinrich [126], L. Heinrich [112], J. Hejbal [134], M. Helbig [50], A. Held [176], S. Hellesund [17], C.M. Helling [170], S. Hellman [47a,47b], L. Henkelmann [33], A.M. Henriques Correia[37], H. Herde [100], Y. Hernández Jiménez [151], L.M. Herrmann [25], T. Herrmann [50], G. Herten [54], R. Hertenberger [111], L. Hervas [37], M.E. Hesping [102], N.P. Hessey [162a], J. Hessler [112], M. Hidaoui [36b], N. Hidic [136], E. Hill [161], S.J. Hillier [21], J.R. Hinds [109], F. Hinterkeuser [25], M. Hirose [127], S. Hirose [163], D. Hirschbuehl [177], T.G. Hitchings [103], B. Hiti [95], J. Hobbs [151], R. Hobincu [29e], N. Hod [175], A.M. Hodges [168], M.C. Hodgkinson [145], B.H. Hodkinson [129], A. Hoecker [37], D.D. Hofer [108], J. Hofer [169], M. Holzbock [37], L.B.A.H. Hommels [33], V. Homsak [129], B.P. Honan [103], J.J. Hong [68], T.M. Hong [132], B.H. Hooberman [168], W.H. Hopkins [6], M.C. Hoppesch [168], Y. Horii [113], M.E. Horstmann [112], S. Hou [154], M.R. Housenga [168], A.S. Howard [95], J. Howarth [59], J. Hoya [6], M. Hrabovsky [125], T. Hryn'ova [4], P.J. Hsu [65], S.-C. Hsu [142], T. Hsu [66], M. Hu [18a], Q. Hu [62], S. Huang [33], X. Huang [14,114c], Y. Huang [136], Y. Huang [114b], Y. Huang [102], Y. Huang [14], Z. Huang [66], Z. Hubacek [135], M. Huebner [25], F. Huegging [25], T.B. Huffman [129], M. Hufnagel Maranha De Faria [83a], C.A. Hugli [48], M. Huhtinen [37], S.K. Huiberts [17], R. Hulsken [106], C.E. Hultquist [18a], N. Huseynov [12,g], J. Huston [109], J. Huth [61], R. Hyneman [7], G. Iacobucci [56], G. Iakovidis [27b], L. Iconomidou-Fayard [66], J.P. Iddon [37], P. Iengo [72a,72b], R. Iguchi [159], Y. Iiyama [159], T. Iizawa [159], Y. Ikegami [84], D. Iliadis [158], N. Ilic [161], H. Imam [36a], G. Inacio Goncalves [83d], S.A. Infante Cabanas [140c], T. Ingebretsen Carlson [47a,47b], J.M. Inglis [96], G. Introzzi [73a,73b], M. Iodice [77a], V. Ippolito [75a,75b], R.K. Irwin [94], M. Ishino [159], W. Islam [176], C. Issever [19], S. Istin [22a,an], K. Itabashi [84], H. Ito [174], R. Iuppa [78a,78b], A. Ivina [175], V. Izzo [72a], P. Jacka [134], P. Jackson [1], P. Jain [48], K. Jakobs [54], T. Jakoubek [175], J. Jamieson [59], W. Jang [159], S. Jankovych [136], M. Javurkova [105], P. Jawahar [103], L. Jeanty [126], J. Jejelava [155a,af], P. Jenni [54,f], C.E. Jessiman [35], C. Jia [143a], H. Jia [170], J. Jia [151], X. Jia [14,114c], Z. Jia [114a], C. Jiang [52], Q. Jiang [64b], S. Jiggins [48], M. Jimenez Ortega [169], J. Jimenez Pena [13], S. Jin [114a], A. Jinaru [29b], O. Jinnouchi [141], P. Johansson [145], K.A. Johns [7], J.W. Johnson [139], F.A. Jolly [48], D.M. Jones [152], E. Jones [48], K.S. Jones[8], P. Jones [33], R.W.L. Jones [93], T.J. Jones [94], H.L. Joos [55,37], R. Joshi [122], J. Jovicevic [16], X. Ju [18a], J.J. Junggeburth [37], T. Junkermann [63a], A. Juste Rozas [13,y], M.K. Juzek [87], S. Kabana [140e], A. Kaczmarska [87], M. Kado [112], H. Kagan [122], M. Kagan [149], A. Kahn [131], C. Kahra [102], T. Kaji [159], E. Kajomovitz [156], N. Kakati [175], N. Kakoty [13], I. Kalaitzidou [54], S. Kandel [8], N.J. Kang [139], D. Kar [34g], K. Karava [129], E. Karentzos [25], O. Karkout [117], S.N. Karpov [39], Z.M. Karpova [39], V. Kartvelishvili [93], A.N. Karyukhin [38], E. Kasimi [158], J. Katzy [48], S. Kaur [35], K. Kawade [146], M.P. Kawale [123], C. Kawamoto [89],

T. Kawamoto [62], E.F. Kay [37], F.I. Kaya [164], S. Kazakos [109], V.F. Kazanin [38], J.M. Keaveney [34a], R. Keeler [171], G.V. Kehris [61], J.S. Keller [35], J.J. Kempster [152], O. Kepka [134], J. Kerr [162b], B.P. Kerridge [137], B.P. Kerševan [95], L. Keszeghova [30a], R.A. Khan [132], A. Khanov [124], A.G. Kharlamov [38], T. Kharlamova [38], E.E. Khoda [142], M. Kholodenko [133a], T.J. Khoo [19], G. Khoriauli [172], Y. Khoulaki [36a], J. Khubua [155b,*], Y.A.R. Khwaira [130], B. Kibirige[34g], D. Kim [6], D.W. Kim [47a,47b], Y.K. Kim [40], N. Kimura [98], M.K. Kingston [55], A. Kirchhoff [55], C. Kirfel [25], F. Kirfel [25], J. Kirk [137], A.E. Kiryunin [112], S. Kita [163], O. Kivernyk [25], M. Klassen [164], C. Klein [35], L. Klein [172], M.H. Klein [45], S.B. Klein [56], U. Klein [94], A. Klimentov [27b], T. Klioutchnikova [37], P. Kluit [117], S. Kluth [112], E. Kneringer [79], T.M. Knight [161], A. Knue [49], M.B. Knuesel [27a], M. Kobel [50], D. Kobylianskii [175], S.F. Koch [129], M. Kocian [149], P. Kodyš [136], D.M. Koeck [126], T. Koffas [35], O. Kolay [50], I. Koletsou [4], T. Komarek [87], K. Köneke [55], A.X.Y. Kong [1], T. Kono [121], N. Konstantinidis [98], P. Kontaxakis [56], B. Konya [100], R. Kopeliansky [42], S. Koperny [86a], K. Korcyl [87], K. Kordas [158,d], A. Korn [98], S. Korn [55], I. Korolkov [13], N. Korotkova [38], B. Kortman [117], O. Kortner [112], S. Kortner [112], W.H. Kostecka [118], M. Kostov [30a], V.V. Kostyukhin [147], A. Kotsokechagia [37], A. Kotwal [51], A. Koulouris [37], A. Kourkoumeli-Charalampidi [73a,73b], C. Kourkoumelis [9], E. Kourlitis [112], O. Kovanda [126], R. Kowalewski [171], W. Kozanecki [126], A.S. Kozhin [38], V.A. Kramarenko [38], G. Kramberger [95], P. Kramer [25], M.W. Krasny [130], A. Krasznahorkay [105], A.C. Kraus [118], J.W. Kraus [177], J.A. Kremer [48], N.B. Krengel [147], T. Kresse [50], L. Kretschmann [177], J. Kretzschmar [94], K. Kreul [19], P. Krieger [161], K. Krizka [21], K. Kroeninger [49], H. Kroha [112], J. Kroll [134], J. Kroll [131], K.S. Krowpman [109], U. Kruchonak [39], H. Krüger [25], N. Krumnack[81], M.C. Kruse [51], O. Kuchinskaia [39], S. Kuday [3a], S. Kuehn [37], R. Kuesters [54], T. Kuhl [48], V. Kukhtin [39], Y. Kulchitsky [39], S. Kuleshov [140d,140b], J. Kull [1], M. Kumar [34g], N. Kumari [48], P. Kumari [162b], A. Kupco [134], T. Kupfer[49], A. Kupich [38], O. Kuprash [54], H. Kurashige [85], L.L. Kurchaninov [162a], O. Kurdysh [4], Y.A. Kurochkin [38], A. Kurova [38], M. Kuze [141], A.K. Kvam [105], J. Kvita [125], N.G. Kyriacou [108], C. Lacasta [169], F. Lacava [75a,75b], H. Lacker [19], D. Lacour [130], N.N. Lad [98], E. Ladygin [39], A. Lafarge [41], B. Laforge [130], T. Lagouri [178], F.Z. Lahbabi [36a], S. Lai [55], J.E. Lambert [171], S. Lammers [68], W. Lampl [7], C. Lampoudis [158,d], G. Lamprinoudis [102], A.N. Lancaster [118], E. Lançon [27b], U. Landgraf [54], M.P.J. Landon [96], V.S. Lang [54], O.K.B. Langrekken [128], A.J. Lankford [165], F. Lanni [37], K. Lantzsch [25], A. Lanza [73a], M. Lanzac Berrocal [169], J.F. Laporte [138], T. Lari [71a], D. Larsen [17], L. Larson [11], F. Lasagni Manghi [24b], M. Lassnig [37], S.D. Lawlor [145], R. Lazaridou[173], M. Lazzaroni [71a,71b], H.D.M. Le [109], E.M. Le Boulicaut [178], L.T. Le Pottier [18a], B. Leban [24b,24a], F. Ledroit-Guillon [60], T.F. Lee [162b], L.L. Leeuw [34c], M. Lefebvre [171], C. Leggett [18a], G. Lehmann Miotto [37], M. Leigh [56], W.A. Leight [105], W. Leinonen [116], A. Leisos [158,v], M.A.L. Leite [83c], C.E. Leitgeb [19], R. Leitner [136], K.J.C. Leney [45], T. Lenz [25], S. Leone [74a], C. Leonidopoulos [52], A. Leopold [150], J.H. Lepage Bourbonnais [35], R. Les [109], C.G. Lester [33], M. Levchenko [38], J. Levêque [4], L.J. Levinson [175], G. Levrini [24b,24a], M.P. Lewicki [87], C. Lewis [142], D.J. Lewis [4], L. Lewitt [145], A. Li [27b], B. Li [143a], C. Li[108], C-Q. Li [112], H. Li [143a], H. Li [103], H. Li [15], H. Li[62], H. Li [143a], J. Li [144a], K. Li [14], L. Li [144a], R. Li [178], S. Li [14,114c], S. Li [144b,144a], T. Li [5], X. Li [106], Z. Li [159], Z. Li [14,114c], Z. Li [62], S. Liang [14,114c], Z. Liang [14], M. Liberatore [138], B. Liberti [76a], K. Lie [64c], J. Lieber Marin [83e], H. Lien [68], H. Lin [108], S.F. Lin [151], L. Linden [111], R.E. Lindley [7], J.H. Lindon [37], J. Ling [61], E. Lipeles [131], A. Lipniacka [17], A. Lister [170], J.D. Little [68], B. Liu [14], B.X. Liu [114b], D. Liu [144b,144a], E.H.L. Liu [21], J.K.K. Liu [120], K. Liu [144b], K. Liu [144b,144a], M. Liu [62], M.Y. Liu [62], P. Liu [14], Q. Liu [144b,142,144a], X. Liu [62], X. Liu [143a], Y. Liu [114b,114c], Y.L. Liu [143a], Y.W. Liu [62], Z. Liu [66,l], S.L. Lloyd [96], E.M. Lobodzinska [48], P. Loch [7], E. Lodhi [161], T. Lohse [19],

K. Lohwasser [145], E. Loiacono [48], J.D. Lomas [21], J.D. Long [42], I. Longarini [165], R. Longo [168], A. Lopez Solis [13], N.A. Lopez-canelas [7], N. Lorenzo Martinez [4], A.M. Lory [111], M. Losada [119a], G. Löschcke Centeno [152], X. Lou [47a,47b], X. Lou [14,114c], A. Lounis [66], P.A. Love [93], G. Lu [14,114c], M. Lu [66], S. Lu [131], Y.J. Lu [154], H.J. Lubatti [142], C. Luci [75a,75b], F.L. Lucio Alves [114a], F. Luehring [68], B.S. Lunday [131], O. Lundberg [150], J. Lunde [37], N.A. Luongo [6], M.S. Lutz [37], A.B. Lux [26], D. Lynn [27b], R. Lysak [134], V. Lysenko [135], E. Lytken [100], V. Lyubushkin [39], T. Lyubushkina [39], M.M. Lyukova [151], M.Firdaus M. Soberi [52], H. Ma [27b], K. Ma [62], L.L. Ma [143a], W. Ma [62], Y. Ma [124], J.C. MacDonald [102], P.C. Machado De Abreu Farias [83e], R. Madar [41], T. Madula [98], J. Maeda [85], T. Maeno [27b], P.T. Mafa [34c,k], H. Maguire [145], V. Maiboroda [66], A. Maio [133a,133b,133d], K. Maj [86a], O. Majersky [48], S. Majewski [126], R. Makhmanazarov [38], N. Makovec [66], V. Maksimovic [16], B. Malaescu [130], J. Malamant[128], Pa. Malecki [87], V.P. Maleev [38], F. Malek [60,p], M. Mali [95], D. Malito [97], U. Mallik [80,*], A. Maloizel [5], S. Maltezos[10], A. Malvezzi Lopes [83d], S. Malyukov[39], J. Mamuzic [13], G. Mancini [53], M.N. Mancini [28], G. Manco [73a,73b], J.P. Mandalia [96], S.S. Mandarry [152], I. Mandić [95], L. Manhaes de Andrade Filho [83a], I.M. Maniatis [175], J. Manjarres Ramos [91], D.C. Mankad [175], A. Mann [111], T. Manoussos [37], M.N. Mantinan [40], S. Manzoni [37], L. Mao [144a], X. Mapekula [34c], A. Marantis [158], R.R. Marcelo Gregorio [96], G. Marchiori [5], M. Marcisovsky [134], C. Marcon [71a], E. Maricic [16], M. Marinescu [48], S. Marium [48], M. Marjanovic [123], A. Markhoos [54], M. Markovitch [66], M.K. Maroun [105], G.T. Marsden[103], E.J. Marshall [93], Z. Marshall [18a], S. Marti-Garcia [169], J. Martin [98], T.A. Martin [137], V.J. Martin [52], B. Martin dit Latour [17], L. Martinelli [75a,75b], M. Martinez [13,y], P. Martinez Agullo [169], V.I. Martinez Outschoorn [105], P. Martinez Suarez [13], S. Martin-Haugh [137], G. Martinovicova [136], V.S. Martoiu [29b], A.C. Martyniuk [98], A. Marzin [37], D. Mascione [78a,78b], L. Masetti [102], J. Masik [103], A.L. Maslennikov [39], S.L. Mason [42], P. Massarotti [72a,72b], P. Mastrandrea [74a,74b], A. Mastroberardino [44b,44a], T. Masubuchi [127], T.T. Mathew [126], J. Matousek [136], D.M. Mattern [49], J. Maurer [29b], T. Maurin [59], A.J. Maury [66], B. Maček [95], C. Mavungu Tsava [104], D.A. Maximov [38], A.E. May [103], E. Mayer [41], R. Mazini [34g], I. Maznas [118], S.M. Mazza [139], E. Mazzeo [71a,71b], J.P. Mc Gowan [171], S.P. Mc Kee [108], C.A. Mc Lean [6], C.C. McCracken [170], E.F. McDonald [107], A.E. McDougall [117], L.F. Mcelhinney [93], J.A. Mcfayden [152], R.P. McGovern [131], R.P. Mckenzie [34g], T.C. Mclachlan [48], D.J. Mclaughlin [98], S.J. McMahon [137], C.M. Mcpartland [94], R.A. McPherson [171,ac], S. Mehlhase [111], A. Mehta [94], D. Melini [169], B.R. Mellado Garcia [34g], A.H. Melo [55], F. Meloni [48], A.M. Mendes Jacques Da Costa [103], L. Meng [93], S. Menke [112], M. Mentink [37], E. Meoni [44b,44a], G. Mercado [118], S. Merianos [158], C. Merlassino [69a,69c], C. Meroni [71a,71b], J. Metcalfe [6], A.S. Mete [6], E. Meuser [102], C. Meyer [68], J-P. Meyer [138], Y. Miao[114a], R.P. Middleton [137], M. Mihovilovic [66], L. Mijović [52], G. Mikenberg [175], M. Mikestikova [134], M. Mikuž [95], H. Mildner [102], A. Milic [37], D.W. Miller [40], E.H. Miller [149], L.S. Miller [35], A. Milov [175], D.A. Milstead[47a,47b], T. Min[114a], A.A. Minaenko [38], I.A. Minashvili [155b], A.I. Mincer [120], B. Mindur [86a], M. Mineev [39], Y. Mino [89], L.M. Mir [13], M. Miralles Lopez [59], M. Mironova [18a], M.C. Missio [116], A. Mitra [173], V.A. Mitsou [169], Y. Mitsumori [113], O. Miu [161], P.S. Miyagawa [96], T. Mkrtchyan [63a], M. Mlinarevic [98], T. Mlinarevic [98], M. Mlynarikova [37], S. Mobius [20], M.H. Mohamed Farook [115], A.F. Mohammed [14,114c], S. Mohapatra [42], S. Mohiuddin [124], G. Mokgatitswane [34g], L. Moleri [175], U. Molinatti [129], L.G. Mollier [20], B. Mondal [147], S. Mondal [135], K. Mönig [48], E. Monnier [104], L. Monsonis Romero[169], J. Montejo Berlingen [13], A. Montella [47a,47b], M. Montella [122], F. Montereali [77a,77b], F. Monticelli [92], S. Monzani [69a,69c], A. Morancho Tarda [43], N. Morange [66], A.L. Moreira De Carvalho [48], M. Moreno Llácer [169], C. Moreno Martinez [56], J.M. Moreno Perez[23b],

P. Morettini[57b], S. Morgenstern[37], M. Morii[61], M. Morinaga[159], M. Moritsu[90],
F. Morodei[75a,75b], P. Moschovakos[37], B. Moser[54], M. Mosidze[155b], T. Moskalets[45],
P. Moskvitina[116], J. Moss[32], P. Moszkowicz[86a], A. Moussa[36d], Y. Moyal[175],
H. Moyano Gomez[13], E.J.W. Moyse[105], O. Mtintsilana[34g], S. Muanza[104], M. Mucha[25],
J. Mueller[132], R. Müller[37], G.A. Mullier[167], A.J. Mullin[33], J.J. Mullin[51], A.E. Mulski[61],
D.P. Mungo[161], D. Munoz Perez[169], F.J. Munoz Sanchez[103], W.J. Murray[173,137],
M. Muškinja[95], C. Mwewa[48], A.G. Myagkov[38,a], A.J. Myers[8], G. Myers[108], M. Myska[135],
B.P. Nachman[18a], K. Nagai[129], K. Nagano[84], R. Nagasaka[159], J.L. Nagle[27b,ak], E. Nagy[104],
A.M. Nairz[37], Y. Nakahama[84], K. Nakamura[84], K. Nakkalil[5], H. Nanjo[127],
E.A. Narayanan[45], Y. Narukawa[159], I. Naryshkin[38], L. Nasella[71a,71b], S. Nasri[119b],
C. Nass[25], G. Navarro[23a], J. Navarro-Gonzalez[169], A. Nayaz[19], P.Y. Nechaeva[38],
S. Nechaeva[24b,24a], F. Nechansky[134], L. Nedic[129], T.J. Neep[21], A. Negri[73a,73b],
M. Negrini[24b], C. Nellist[117], C. Nelson[106], K. Nelson[108], S. Nemecek[134], M. Nessi[37,h],
M.S. Neubauer[168], J. Newell[94], P.R. Newman[21], Y.W.Y. Ng[168], B. Ngair[119a],
H.D.N. Nguyen[110], J.D. Nichols[123], R.B. Nickerson[129], R. Nicolaidou[138], J. Nielsen[139],
M. Niemeyer[55], J. Niermann[37], N. Nikiforou[37], V. Nikolaenko[38,a], I. Nikolic-Audit[130],
P. Nilsson[27b], I. Ninca[48], G. Ninio[157], A. Nisati[75a], N. Nishu[2], R. Nisius[112],
N. Nitika[69a,69c], J-E. Nitschke[50], E.K. Nkadimeng[34b], T. Nobe[159], T. Nommensen[153],
M.B. Norfolk[145], B.J. Norman[35], M. Noury[36a], J. Novak[95], T. Novak[95], R. Novotny[135],
L. Nozka[125], K. Ntekas[165], N.M.J. Nunes De Moura Junior[83b], J. Ocariz[130], A. Ochi[85],
I. Ochoa[133a], S. Oerdek[48,z], J.T. Offermann[40], A. Ogrodnik[136], A. Oh[103], C.C. Ohm[150],
H. Oide[84], M.L. Ojeda[37], Y. Okumura[159], L.F. Oleiro Seabra[133a], I. Oleksiyuk[56],
G. Oliveira Correa[13], D. Oliveira Damazio[27b], J.L. Oliver[165], Ö.O. Öncel[54], A.P. O'Neill[20],
A. Onofre[133a,133e,e], P.U.E. Onyisi[11], M.J. Oreglia[40], D. Orestano[77a,77b], R. Orlandini[77a,77b],
R.S. Orr[161], L.M. Osojnak[131], Y. Osumi[113], G. Otero y Garzon[31], H. Otono[90],
G.J. Ottino[18a], M. Ouchrif[36d], F. Ould-Saada[128], T. Ovsiannikova[142], M. Owen[59],
R.E. Owen[137], V.E. Ozcan[22a], F. Ozturk[87], N. Ozturk[8], S. Ozturk[82], H.A. Pacey[129],
K. Pachal[162a], A. Pacheco Pages[13], C. Padilla Aranda[13], G. Padovano[75a,75b],
S. Pagan Griso[18a], G. Palacino[68], A. Palazzo[70a,70b], J. Pampel[25], J. Pan[178], T. Pan[64a],
D.K. Panchal[11], C.E. Pandini[117], J.G. Panduro Vazquez[137], H.D. Pandya[1], H. Pang[138],
P. Pani[48], G. Panizzo[69a,69c], L. Panwar[130], L. Paolozzi[56], S. Parajuli[168], A. Paramonov[6],
C. Paraskevopoulos[53], D. Paredes Hernandez[64b], A. Pareti[73a,73b], K.R. Park[42], T.H. Park[112],
F. Parodi[57b,57a], J.A. Parsons[42], U. Parzefall[54], B. Pascual Dias[41], L. Pascual Dominguez[101],
E. Pasqualucci[75a], S. Passaggio[57b], F. Pastore[97], P. Patel[87], U.M. Patel[51], J.R. Pater[103],
T. Pauly[37], F. Pauwels[136], C.I. Pazos[164], M. Pedersen[128], R. Pedro[133a], S.V. Peleganchuk[38],
O. Penc[37], E.A. Pender[52], S. Peng[15], G.D. Penn[178], K.E. Penski[111], M. Penzin[38],
B.S. Peralva[83d], A.P. Pereira Peixoto[142], L. Pereira Sanchez[149], D.V. Perepelitsa[27b,ak],
G. Perera[105], E. Perez Codina[162a], M. Perganti[10], H. Pernegger[37], S. Perrella[75a,75b],
O. Perrin[41], K. Peters[48], R.F.Y. Peters[103], B.A. Petersen[37], T.C. Petersen[43], E. Petit[104],
V. Petousis[135], A.R. Petri[71a,71b], C. Petridou[158,d], T. Petru[136], A. Petrukhin[147], M. Pettee[18a],
A. Petukhov[82], K. Petukhova[37], R. Pezoa[140f], L. Pezzotti[24b,24a], G. Pezzullo[178],
L. Pfaffenbichler[37], A.J. Pfleger[37], T.M. Pham[176], T. Pham[107], P.W. Phillips[137],
G. Piacquadio[151], E. Pianori[18a], F. Piazza[126], R. Piegaia[31], D. Pietreanu[29b],
A.D. Pilkington[103], M. Pinamonti[69a,69c], J.L. Pinfold[2], B.C. Pinheiro Pereira[133a],
J. Pinol Bel[13], A.E. Pinto Pinoargote[130], L. Pintucci[69a,69c], K.M. Piper[152], A. Pirttikoski[56],
D.A. Pizzi[35], L. Pizzimento[64b], A. Plebani[33], M.-A. Pleier[27b], V. Pleskot[136], E. Plotnikova[39],
G. Poddar[96], R. Poettgen[100], L. Poggioli[130], S. Polacek[136], G. Polesello[73a], A. Poley[148],

A. Polini[24b], C.S. Pollard[173], Z.B. Pollock[122], E. Pompa Pacchi[123], N.I. Pond[98], D. Ponomarenko[68], L. Pontecorvo[37], S. Popa[29a], G.A. Popeneciu[29d], A. Poreba[37], D.M. Portillo Quintero[162a], S. Pospisil[135], M.A. Postill[145], P. Postolache[29c], K. Potamianos[173], P.A. Potepa[86a], I.N. Potrap[39], C.J. Potter[33], H. Potti[153], J. Poveda[169], M.E. Pozo Astigarraga[37], R. Pozzi[37], A. Prades Ibanez[76a,76b], J. Pretel[171], D. Price[103], M. Primavera[70a], L. Primomo[69a,69c], M.A. Principe Martin[101], R. Privara[125], T. Procter[86b], M.L. Proffitt[142], N. Proklova[131], K. Prokofiev[64c], G. Proto[112], J. Proudfoot[6], M. Przybycien[86a], W.W. Przygoda[86b], A. Psallidas[46], J.E. Puddefoot[145], D. Pudzha[53], D. Pyatiizbyantseva[116], J. Qian[108], R. Qian[109], D. Qichen[103], Y. Qin[13], T. Qiu[52], A. Quadt[55], M. Queitsch-Maitland[103], G. Quetant[56], R.P. Quinn[170], G. Rabanal Bolanos[61], D. Rafanoharana[54], F. Raffaeli[76a,76b], F. Ragusa[71a,71b], J.L. Rainbolt[40], J.A. Raine[56], S. Rajagopalan[27b], E. Ramakoti[39], L. Rambelli[57b,57a], I.A. Ramirez-Berend[35], K. Ran[48,114c], D.S. Rankin[131], N.P. Rapheeha[34g], H. Rasheed[29b], D.F. Rassloff[63a], A. Rastogi[18a], S. Rave[102], S. Ravera[57b,57a], B. Ravina[37], I. Ravinovich[175], M. Raymond[37], A.L. Read[128], N.P. Readioff[145], D.M. Rebuzzi[73a,73b], A.S. Reed[112], K. Reeves[28], J.A. Reidelsturz[177], D. Reikher[126], A. Rej[49], C. Rembser[37], H. Ren[62], M. Renda[29b], F. Renner[48], A.G. Rennie[59], A.L. Rescia[48], S. Resconi[71a], M. Ressegotti[57b,57a], S. Rettie[37], W.F. Rettie[35], E. Reynolds[18a], O.L. Rezanova[39], P. Reznicek[136], H. Riani[36d], N. Ribaric[51], E. Ricci[78a,78b], R. Richter[112], S. Richter[47a,47b], E. Richter-Was[86b], M. Ridel[130], S. Ridouani[36d], P. Rieck[120], P. Riedler[37], E.M. Riefel[47a,47b], J.O. Rieger[117], M. Rijssenbeek[151], M. Rimoldi[37], L. Rinaldi[24b,24a], P. Rincke[167], G. Ripellino[167], I. Riu[13], J.C. Rivera Vergara[171], F. Rizatdinova[124], E. Rizvi[96], B.R. Roberts[18a], S.S. Roberts[139], D. Robinson[33], M. Robles Manzano[102], A. Robson[59], A. Rocchi[76a,76b], C. Roda[74a,74b], S. Rodriguez Bosca[37], Y. Rodriguez Garcia[23a], A.M. Rodríguez Vera[118], S. Roe[37], J.T. Roemer[37], O. Røhne[128], R.A. Rojas[37], C.P.A. Roland[130], A. Romaniouk[79], E. Romano[73a,73b], M. Romano[24b], A.C. Romero Hernandez[168], N. Rompotis[94], L. Roos[130], S. Rosati[75a], B.J. Rosser[40], E. Rossi[129], E. Rossi[72a,72b], L.P. Rossi[61], L. Rossini[54], R. Rosten[122], M. Rotaru[29b], B. Rottler[54], D. Rousseau[66], D. Rousso[48], S. Roy-Garand[161], A. Rozanov[104], Z.M.A. Rozario[59], Y. Rozen[156], A. Rubio Jimenez[169], V.H. Ruelas Rivera[19], T.A. Ruggeri[1], A. Ruggiero[129], A. Ruiz-Martinez[169], A. Rummler[37], Z. Rurikova[54], N.A. Rusakovich[39], H.L. Russell[171], G. Russo[75a,75b], J.P. Rutherfoord[7], S. Rutherford Colmenares[33], M. Rybar[136], P. Rybczynski[86a], A. Ryzhov[45], J.A. Sabater Iglesias[56], H.F-W. Sadrozinski[139], F. Safai Tehrani[75a], S. Saha[1], M. Sahinsoy[82], B. Sahoo[175], A. Saibel[169], B.T. Saifuddin[123], M. Saimpert[138], G.T. Saito[83c], M. Saito[159], T. Saito[159], A. Sala[71a,71b], A. Salnikov[149], J. Salt[169], A. Salvador Salas[157], F. Salvatore[152], A. Salzburger[37], D. Sammel[54], E. Sampson[93], D. Sampsonidis[158,d], D. Sampsonidou[126], J. Sánchez[169], V. Sanchez Sebastian[169], H. Sandaker[128], C.O. Sander[48], J.A. Sandesara[176], M. Sandhoff[177], C. Sandoval[23b], L. Sanfilippo[63a], D.P.C. Sankey[137], T. Sano[89], A. Sansoni[53], L. Santi[37], C. Santoni[41], H. Santos[133a,133b], A. Santra[175], E. Sanzani[24b,24a], K.A. Saoucha[88b], J.G. Saraiva[133a,133d], J. Sardain[7], O. Sasaki[84], K. Sato[163], C. Sauer[37], E. Sauvan[4], P. Savard[161,ai], R. Sawada[159], C. Sawyer[137], L. Sawyer[99], C. Sbarra[24b], A. Sbrizzi[24b,24a], T. Scanlon[98], J. Schaarschmidt[142], U. Schäfer[102], A.C. Schaffer[66,45], D. Schaile[111], R.D. Schamberger[151], C. Scharf[19], M.M. Schefer[20], V.A. Schegelsky[38], D. Scheirich[136], M. Schernau[140e], C. Scheulen[56], C. Schiavi[57b,57a], M. Schioppa[44b,44a], B. Schlag[149], S. Schlenker[37], J. Schmeing[177], E. Schmidt[112], M.A. Schmidt[177], K. Schmieden[102], C. Schmitt[102], N. Schmitt[102], S. Schmitt[48], L. Schoeffel[138], A. Schoening[63b], P.G. Scholer[35], E. Schopf[147], M. Schott[25], S. Schramm[56], T. Schroer[56],

H-C. Schultz-Coulon [63a], M. Schumacher [54], B.A. Schumm [139], Ph. Schune [138],
H.R. Schwartz [139], A. Schwartzman [149], T.A. Schwarz [108], Ph. Schwemling [138],
R. Schwienhorst [109], F.G. Sciacca [20], A. Sciandra [27b], G. Sciolla [28], F. Scuri [74a],
C.D. Sebastiani [37], K. Sedlaczek [118], S.C. Seidel [115], A. Seiden [139], B.D. Seidlitz [42], C. Seitz [48],
J.M. Seixas [83b], G. Sekhniaidze [72a], L. Selem [60], N. Semprini-Cesari [24b,24a], A. Semushin [179],
D. Sengupta [56], V. Senthilkumar [169], L. Serin [66], M. Sessa [76a,76b], H. Severini [123],
F. Sforza [57b,57a], A. Sfyrla [56], Q. Sha [14], E. Shabalina [55], H. Shaddix [118], A.H. Shah [33],
R. Shaheen [150], J.D. Shahinian [131], M. Shamim [37], L.Y. Shan [14], M. Shapiro [18a], A. Sharma [37],
A.S. Sharma [170], P. Sharma [27b], P.B. Shatalov [38], K. Shaw [152], S.M. Shaw [103], Q. Shen [144a],
D.J. Sheppard [148], P. Sherwood [98], L. Shi [98], X. Shi [14], S. Shimizu [84], C.O. Shimmin [178],
I.P.J. Shipsey [129,*], S. Shirabe [90], M. Shiyakova [39,aa], M.J. Shochet [40], D.R. Shope [128],
B. Shrestha [123], S. Shrestha [122,am], I. Shreyber [39], M.J. Shroff [171], P. Sicho [134], A.M. Sickles [168],
E. Sideras Haddad [34g,166], A.C. Sidley [117], A. Sidoti [24b], F. Siegert [50], Dj. Sijacki [16], F. Sili [92],
J.M. Silva [52], I. Silva Ferreira [83b], M.V. Silva Oliveira [27b], S.B. Silverstein [47a], S. Simion[66],
R. Simoniello [37], E.L. Simpson [103], H. Simpson [152], L.R. Simpson [6], S. Simsek [82],
S. Sindhu [55], P. Sinervo [161], S.N. Singh [28], S. Singh [27b], S. Sinha [48], S. Sinha [103],
M. Sioli [24b,24a], K. Sioulas [9], I. Siral [37], E. Sitnikova [48], J. Sjölin [47a,47b], A. Skaf [55],
E. Skorda [21], P. Skubic [123], M. Slawinska [87], I. Slazyk [17], V. Smakhtin[175], B.H. Smart [137],
S.Yu. Smirnov [140b], Y. Smirnov [82], L.N. Smirnova [38,a], O. Smirnova [100], A.C. Smith [42],
D.R. Smith[165], J.L. Smith [103], M.B. Smith [35], R. Smith[149], H. Smitmanns [102], M. Smizanska [93],
K. Smolek [135], P. Smolyanskiy [135], A.A. Snesarev [39], H.L. Snoek [117], S. Snyder [27b],
R. Sobie [171,ac], A. Soffer [157], C.A. Solans Sanchez [37], E.Yu. Soldatov [39], U. Soldevila [169],
A.A. Solodkov [34g], S. Solomon [28], A. Soloshenko [39], K. Solovieva [54], O.V. Solovyanov [41],
P. Sommer [50], A. Sonay [13], A. Sopczak [135], A.L. Sopio [52], F. Sopkova [30b], J.D. Sorenson [115],
I.R. Sotarriva Alvarez [141], V. Sothilingam[63a], O.J. Soto Sandoval [140c,140b], S. Sottocornola [68],
R. Soualah [88a], Z. Soumaimi [36e], D. South [48], N. Soybelman [175], S. Spagnolo [70a,70b],
M. Spalla [112], D. Sperlich [54], B. Spisso [72a,72b], D.P. Spiteri [59], L. Splendori [104], M. Spousta [136],
E.J. Staats [35], R. Stamen [63a], E. Stanecka [87], W. Stanek-Maslouska [48], M.V. Stange [50],
B. Stanislaus [18a], M.M. Stanitzki [48], B. Stapf [48], E.A. Starchenko [38], G.H. Stark [139], J. Stark [91],
P. Staroba [134], P. Starovoitov [88b], R. Staszewski [87], G. Stavropoulos [46], A. Stefl [37],
P. Steinberg [27b], B. Stelzer [148,162a], H.J. Stelzer [132], O. Stelzer-Chilton [162a], H. Stenzel [58],
T.J. Stevenson [152], G.A. Stewart [37], J.R. Stewart [124], M.C. Stockton [37], G. Stoicea [29b],
M. Stolarski [133a], S. Stonjek [112], A. Straessner [50], J. Strandberg [150], S. Strandberg [47a,47b],
M. Stratmann [177], M. Strauss [123], T. Strebler [104], P. Strizenec [30b], R. Ströhmer [172],
D.M. Strom [126], R. Stroynowski [45], A. Strubig [47a,47b], S.A. Stucci [27b], B. Stugu [17],
J. Stupak [123], N.A. Styles [48], D. Su [149], S. Su [62], X. Su [62], D. Suchy [30a], K. Sugizaki [131],
V.V. Sulin [38], M.J. Sullivan [94], D.M.S. Sultan [129], L. Sultanaliyeva [38], S. Sultansoy [3b],
S. Sun [176], W. Sun [14], O. Sunneborn Gudnadottir [167], N. Sur [100], M.R. Sutton [152],
H. Suzuki [163], M. Svatos [134], P.N. Swallow [33], M. Swiatlowski [162a], T. Swirski [172],
I. Sykora [30a], M. Sykora [136], T. Sykora [136], D. Ta [102], K. Tackmann [48,z], A. Taffard [165],
R. Tafirout [162a], Y. Takubo [84], M. Talby [104], A.A. Talyshev [38], K.C. Tam [64b], N.M. Tamir [157],
A. Tanaka [159], J. Tanaka [159], R. Tanaka [66], M. Tanasini [151], Z. Tao [170], S. Tapia Araya [140f],
S. Tapprogge [102], A. Tarek Abouelfadl Mohamed [109], S. Tarem [156], K. Tariq [14], G. Tarna [29b],
G.F. Tartarelli [71a], M.J. Tartarin [91], P. Tas [136], M. Tasevsky [134], E. Tassi [44b,44a], A.C. Tate [168],
G. Tateno [159], Y. Tayalati [36e,ab], G.N. Taylor [107], W. Taylor [162b], A.S. Tegetmeier [91],
P. Teixeira-Dias [97], J.J. Teoh [161], K. Terashi [159], J. Terron [101], S. Terzo [13], M. Testa [53],
R.J. Teuscher [161,ac], A. Thaler [79], O. Theiner [56], T. Theveneaux-Pelzer [104], D.W. Thomas[97],

J.P. Thomas [21], E.A. Thompson [18a], P.D. Thompson [21], E. Thomson [131], R.E. Thornberry [45], C. Tian [62], Y. Tian [56], V. Tikhomirov [82], Yu.A. Tikhonov [39], S. Timoshenko[38], D. Timoshyn [136], E.X.L. Ting [1], P. Tipton [178], A. Tishelman-Charny [27b], K. Todome [141], S. Todorova-Nova [136], S. Todt[50], L. Toffolin [69a,69c], M. Togawa [84], J. Tojo [90], S. Tokár [30a], O. Toldaiev [68], G. Tolkachev [104], M. Tomoto [84,113], L. Tompkins [149,o], E. Torrence [126], H. Torres [91], E. Torró Pastor [169], M. Toscani [31], C. Tosciri [40], M. Tost [11], D.R. Tovey [145], T. Trefzger [172], P.M. Tricarico [13], A. Tricoli [27b], I.M. Trigger [162a], S. Trincaz-Duvoid [130], D.A. Trischuk [28], A. Tropina[39], L. Truong [34c], M. Trzebinski [87], A. Trzupek [87], F. Tsai [151], M. Tsai [108], A. Tsiamis [158], P.V. Tsiareshka[39], S. Tsigaridas [162a], A. Tsirigotis [158,v], V. Tsiskaridze [161], E.G. Tskhadadze [155a], M. Tsopoulou [158], Y. Tsujikawa [89], I.I. Tsukerman [38], V. Tsulaia [18a], S. Tsuno [84], K. Tsuri [121], D. Tsybychev [151], Y. Tu [64b], A. Tudorache [29b], V. Tudorache [29b], S. Turchikhin [57b,57a], I. Turk Cakir [3a], R. Turra [71a], T. Turtuvshin [39,ad], P.M. Tuts [42], S. Tzamarias [158,d], E. Tzovara [102], Y. Uematsu [84], F. Ukegawa [163], P.A. Ulloa Poblete [140c,140b], E.N. Umaka [27b], G. Unal [37], A. Undrus [27b], G. Unel [165], J. Urban [30b], P. Urrejola [140a], G. Usai [8], R. Ushioda [160], M. Usman [110], F. Ustuner [52], Z. Uysal [82], V. Vacek [135], B. Vachon [106], T. Vafeiadis [37], A. Vaitkus [98], C. Valderanis [111], E. Valdes Santurio [47a,47b], M. Valente [37], S. Valentinetti [24b,24a], A. Valero [169], E. Valiente Moreno [169], A. Vallier [91], J.A. Valls Ferrer [169], D.R. Van Arneman [117], T.R. Van Daalen [142], A. Van Der Graaf [49], H.Z. Van Der Schyf [34g], P. Van Gemmeren [6], M. Van Rijnbach [37], S. Van Stroud [98], I. Van Vulpen [117], P. Vana [136], M. Vanadia [76a,76b], U.M. Vande Voorde [150], W. Vandelli [37], E.R. Vandewall [124], D. Vannicola [157], L. Vannoli [53], R. Vari [75a], E.W. Varnes [7], C. Varni [18b], D. Varouchas [66], L. Varriale [169], K.E. Varvell [153], M.E. Vasile [29b], L. Vaslin[84], M.D. Vassilev [149], A. Vasyukov [39], L.M. Vaughan [124], R. Vavricka[136], T. Vazquez Schroeder [13], J. Veatch [32], V. Vecchio [103], M.J. Veen [105], I. Veliscek [27b], I. Velkovska [95], L.M. Veloce [161], F. Veloso [133a,133c], S. Veneziano [75a], A. Ventura [70a,70b], S. Ventura Gonzalez [138], A. Verbytskyi [112], M. Verducci [74a,74b], C. Vergis [96], M. Verissimo De Araujo [83b], W. Verkerke [117], J.C. Vermeulen [117], C. Vernieri [149], M. Vessella [165], M.C. Vetterli [148,ai], A. Vgenopoulos [102], N. Viaux Maira [140f], T. Vickey [145], O.E. Vickey Boeriu [145], G.H.A. Viehhauser [129], L. Vigani [63b], M. Vigl [112], M. Villa [24b,24a], M. Villaplana Perez [169], E.M. Villhauer[52], E. Vilucchi [53], M.G. Vincter [35], A. Visibile[117], C. Vittori [37], I. Vivarelli [24b,24a], E. Voevodina [112], F. Vogel [111], J.C. Voigt [50], P. Vokac [135], Yu. Volkotrub [86b], E. Von Toerne [25], B. Vormwald [37], K. Vorobev [51], M. Vos [169], K. Voss [147], M. Vozak [37], L. Vozdecky [123], N. Vranjes [16], M. Vranjes Milosavljevic [16], M. Vreeswijk [117], N.K. Vu [144b,144a], R. Vuillermet [37], O. Vujinovic [102], I. Vukotic [40], I.K. Vyas [35], J.F. Wack [33], S. Wada [163], C. Wagner[149], J.M. Wagner [18a], W. Wagner [177], S. Wahdan [177], H. Wahlberg [92], C.H. Waits [123], J. Walder [137], R. Walker [111], W. Walkowiak [147], A. Wall [131], E.J. Wallin [100], T. Wamorkar [18a], A.Z. Wang [139], C. Wang [102], C. Wang [11], H. Wang [18a], J. Wang [64c], P. Wang [103], P. Wang [98], R. Wang [61], R. Wang [6], S.M. Wang [154], S. Wang [14], T. Wang [62], T. Wang [62], W.T. Wang [80], W. Wang [14], X. Wang [168], X. Wang [144a], X. Wang [48], Y. Wang [114a], Y. Wang [62], Z. Wang [108], Z. Wang [144b], Z. Wang [108], C. Wanotayaroj [84], A. Warburton [106], A.L. Warnerbring [147], N. Warrack [59], S. Waterhouse [97], A.T. Watson [21], H. Watson [52], M.F. Watson [21], E. Watton [59], G. Watts [142], B.M. Waugh [98], J.M. Webb [54], C. Weber [27b], H.A. Weber [19], M.S. Weber [20], S.M. Weber [63a], C. Wei [62], Y. Wei [54], A.R. Weidberg [129], E.J. Weik [120], J. Weingarten [49], C. Weiser [54], C.J. Wells [48], T. Wenaus [27b], B. Wendland [49], T. Wengler [37], N.S. Wenke[112], N. Wermes [25], M. Wessels [63a], A.M. Wharton [93], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [165], L. Wickremasinghe [127], W. Wiedenmann [176], M. Wielers [137], R. Wierda [150], C. Wiglesworth [43], H.G. Wilkens [37], J.J.H. Wilkinson [33], D.M. Williams [42], H.H. Williams[131],

S. Williams [33], S. Willocq [105], B.J. Wilson [103], D.J. Wilson [103], P.J. Windischhofer [40], F.I. Winkel [31], F. Winklmeier [126], B.T. Winter [54], M. Wittgen[149], M. Wobisch [99], T. Wojtkowski[60], Z. Wolffs [117], J. Wollrath[37], M.W. Wolter [87], H. Wolters [133a,133c], M.C. Wong[139], E.L. Woodward [42], S.D. Worm [48], B.K. Wosiek [87], K.W. Woźniak [87], S. Wozniewski [55], K. Wraight [59], C. Wu [161], C. Wu [21], J. Wu [159], M. Wu [114b], M. Wu [116], S.L. Wu [176], S. Wu [14], X. Wu [62], Y. Wu [62], Z. Wu [4], J. Wuerzinger [112], T.R. Wyatt [103], B.M. Wynne [52], S. Xella [43], L. Xia [114a], M. Xia [15], M. Xie [62], A. Xiong [126], J. Xiong [18a], D. Xu [14], H. Xu [62], L. Xu [62], R. Xu [131], T. Xu [108], Y. Xu [142], Z. Xu [52], Z. Xu[114a], B. Yabsley [153], S. Yacoob [34a], Y. Yamaguchi [84], E. Yamashita [159], H. Yamauchi [163], T. Yamazaki [18a], Y. Yamazaki [85], S. Yan [59], Z. Yan [105], H.J. Yang [144a,144b], H.T. Yang [62], S. Yang [62], T. Yang [64c], X. Yang [37], X. Yang [14], Y. Yang [159], Y. Yang[62], W-M. Yao [18a], C.L. Yardley [152], J. Ye [14], S. Ye [27b], X. Ye [62], Y. Yeh [98], I. Yeletskikh [39], B. Yeo [18b], M.R. Yexley [98], T.P. Yildirim [129], P. Yin [42], K. Yorita [174], C.J.S. Young [37], C. Young [149], N.D. Young[126], Y. Yu [62], J. Yuan [14,114c], M. Yuan [108], R. Yuan [144b,144a], L. Yue [98], M. Zaazoua [62], B. Zabinski [87], I. Zahir [36a], A. Zaio[57b,57a], Z.K. Zak [87], T. Zakareishvili [169], S. Zambito [56], J.A. Zamora Saa [140d], J. Zang [159], D. Zanzi [54], R. Zanzottera [71a,71b], O. Zaplatilek [135], C. Zeitnitz [177], H. Zeng [14], J.C. Zeng [168], D.T. Zenger Jr [28], O. Zenin [38], T. Ženiš [30a], S. Zenz [96], D. Zerwas [66], M. Zhai [14,114c], D.F. Zhang [145], G. Zhang [14], J. Zhang [143a], J. Zhang [6], K. Zhang [14,114c], L. Zhang [62], L. Zhang [114a], P. Zhang [14,114c], R. Zhang [176], S. Zhang [91], T. Zhang [159], X. Zhang [144a], Y. Zhang [142], Y. Zhang [98], Y. Zhang [62], Y. Zhang [114a], Z. Zhang [18a], Z. Zhang [143a], Z. Zhang [66], H. Zhao [142], T. Zhao [143a], Y. Zhao [35], Z. Zhao [62], Z. Zhao [62], A. Zhemchugov [39], J. Zheng [114a], K. Zheng [168], X. Zheng [62], Z. Zheng [149], D. Zhong [168], B. Zhou [108], H. Zhou [7], N. Zhou [144a], Y. Zhou [15], Y. Zhou [114a], Y. Zhou[7], C.G. Zhu [143a], J. Zhu [108], X. Zhu[144b], Y. Zhu [144a], Y. Zhu [62], X. Zhuang [14], K. Zhukov [68], N.I. Zimine [39], J. Zinsser [63b], M. Ziolkowski [147], L. Živković [16], A. Zoccoli [24b,24a], K. Zoch [61], T.G. Zorbas [145], O. Zormpa [46], L. Zwalinski [37].

[1]Department of Physics, University of Adelaide, Adelaide; Australia.
[2]Department of Physics, University of Alberta, Edmonton AB; Canada.
[3] [(a)]Department of Physics, Ankara University, Ankara; [(b)]Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.
[4]LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
[5]APC, Université Paris Cité, CNRS/IN2P3, Paris; France.
[6]High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
[7]Department of Physics, University of Arizona, Tucson AZ; United States of America.
[8]Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
[9]Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
[10]Physics Department, National Technical University of Athens, Zografou; Greece.
[11]Department of Physics, University of Texas at Austin, Austin TX; United States of America.
[12]Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
[14]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.
[15]Physics Department, Tsinghua University, Beijing; China.
[16]Institute of Physics, University of Belgrade, Belgrade; Serbia.
[17]Department for Physics and Technology, University of Bergen, Bergen; Norway.
[18] [(a)]Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; [(b)]University of California,

Berkeley CA; United States of America.
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
[21]School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
[22][(a)]Department of Physics, Bogazici University, Istanbul;[(b)]Department of Physics Engineering, Gaziantep University, Gaziantep;[(c)]Department of Physics, Istanbul University, Istanbul; Türkiye.
[23][(a)]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;[(b)]Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.
[24][(a)]Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;[(b)]INFN Sezione di Bologna; Italy.
[25]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[26]Department of Physics, Boston University, Boston MA; United States of America.
[27][(a)]University of Colorado Boulder, Department of Physics, Colorado;[(b)]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[28]Department of Physics, Brandeis University, Waltham MA; United States of America.
[29][(a)]Transilvania University of Brasov, Brasov;[(b)]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;[(c)]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;[(d)]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;[(e)]National University of Science and Technology Politechnica, Bucharest;[(f)]West University in Timisoara, Timisoara;[(g)]Faculty of Physics, University of Bucharest, Bucharest; Romania.
[30][(a)]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;[(b)]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[31]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.
[32]California State University, CA; United States of America.
[33]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[34][(a)]Department of Physics, University of Cape Town, Cape Town;[(b)]iThemba Labs, Western Cape;[(c)]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;[(d)]National Institute of Physics, University of the Philippines Diliman (Philippines);[(e)]University of South Africa, Department of Physics, Pretoria;[(f)]University of Zululand, KwaDlangezwa;[(g)]School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
[35]Department of Physics, Carleton University, Ottawa ON; Canada.
[36][(a)]Faculté des Sciences Ain Chock, Université Hassan II de Casablanca;[(b)]Faculté des Sciences, Université Ibn-Tofail, Kénitra;[(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;[(d)]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;[(e)]Faculté des sciences, Université Mohammed V, Rabat;[(f)]Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[37]CERN, Geneva; Switzerland.
[38]Affiliated with an institute formerly covered by a cooperation agreement with CERN.
[39]Affiliated with an international laboratory covered by a cooperation agreement with CERN.
[40]Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
[41]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[42]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[43]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
[44][(a)]Dipartimento di Fisica, Università della Calabria, Rende;[(b)]INFN Gruppo Collegato di Cosenza,

Laboratori Nazionali di Frascati; Italy.
[45]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[46]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
[47(a)]Department of Physics, Stockholm University;[(b)]Oskar Klein Centre, Stockholm; Sweden.
[48]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
[49]Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany.
[50]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
[51]Department of Physics, Duke University, Durham NC; United States of America.
[52]SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
[53]INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
[54]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
[55]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
[56]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[57(a)]Dipartimento di Fisica, Università di Genova, Genova;[(b)]INFN Sezione di Genova; Italy.
[58]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
[59]SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
[60]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
[61]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
[62]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.
[63(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;[(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[64(a)]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;[(b)]Department of Physics, University of Hong Kong, Hong Kong;[(c)]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
[65]Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
[66]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
[67]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
[68]Department of Physics, Indiana University, Bloomington IN; United States of America.
[69(a)]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;[(b)]ICTP, Trieste;[(c)]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
[70(a)]INFN Sezione di Lecce;[(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[71(a)]INFN Sezione di Milano;[(b)]Dipartimento di Fisica, Università di Milano, Milano; Italy.
[72(a)]INFN Sezione di Napoli;[(b)]Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
[73(a)]INFN Sezione di Pavia;[(b)]Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[74(a)]INFN Sezione di Pisa;[(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[75(a)]INFN Sezione di Roma;[(b)]Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[76(a)]INFN Sezione di Roma Tor Vergata;[(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[77(a)]INFN Sezione di Roma Tre;[(b)]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
[78(a)]INFN-TIFPA;[(b)]Università degli Studi di Trento, Trento; Italy.
[79]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
[80]University of Iowa, Iowa City IA; United States of America.
[81]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[82]Istinye University, Sariyer, Istanbul; Türkiye.

[83](a)Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;(c)Instituto de Física, Universidade de São Paulo, São Paulo;(d)Rio de Janeiro State University, Rio de Janeiro;(e)Federal University of Bahia, Bahia; Brazil.
[84]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[85]Graduate School of Science, Kobe University, Kobe; Japan.
[86](a)AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
[87]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[88](a)Khalifa University of Science and Technology, Abu Dhabi;(b)University of Sharjah, Sharjah; United Arab Emirates.
[89]Faculty of Science, Kyoto University, Kyoto; Japan.
[90]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[91]L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[92]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[93]Physics Department, Lancaster University, Lancaster; United Kingdom.
[94]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[95]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[96]Department of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[97]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[98]Department of Physics and Astronomy, University College London, London; United Kingdom.
[99]Louisiana Tech University, Ruston LA; United States of America.
[100]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[101]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[102]Institut für Physik, Universität Mainz, Mainz; Germany.
[103]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[104]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[105]Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[106]Department of Physics, McGill University, Montreal QC; Canada.
[107]School of Physics, University of Melbourne, Victoria; Australia.
[108]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[109]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[110]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[111]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[112]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[113]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
[114](a)Department of Physics, Nanjing University, Nanjing;(b)School of Science, Shenzhen Campus of Sun Yat-sen University;(c)University of Chinese Academy of Science (UCAS), Beijing; China.
[115]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
[116]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
[117]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.

[118]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[119(a)]New York University Abu Dhabi, Abu Dhabi;[(b)]United Arab Emirates University, Al Ain; United Arab Emirates.
[120]Department of Physics, New York University, New York NY; United States of America.
[121]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[122]Ohio State University, Columbus OH; United States of America.
[123]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[124]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[125]Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
[126]Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
[127]Graduate School of Science, University of Osaka, Osaka; Japan.
[128]Department of Physics, University of Oslo, Oslo; Norway.
[129]Department of Physics, Oxford University, Oxford; United Kingdom.
[130]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
[131]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[132]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
[133(a)]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;[(b)]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;[(c)]Departamento de Física, Universidade de Coimbra, Coimbra;[(d)]Centro de Física Nuclear da Universidade de Lisboa, Lisboa;[(e)]Departamento de Física, Escola de Ciências, Universidade do Minho, Braga;[(f)]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);[(g)]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
[134]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
[135]Czech Technical University in Prague, Prague; Czech Republic.
[136]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
[137]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
[138]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[139]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
[140(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;[(b)]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;[(c)]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;[(d)]Universidad Andres Bello, Department of Physics, Santiago;[(e)]Instituto de Alta Investigación, Universidad de Tarapacá, Arica;[(f)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
[141]Department of Physics, Institute of Science, Tokyo; Japan.
[142]Department of Physics, University of Washington, Seattle WA; United States of America.
[143(a)]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;[(b)]School of Physics, Zhengzhou University; China.
[144(a)]State Key Laboratory of Dark Matter Physics, School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;[(b)]State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai; China.
[145]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[146]Department of Physics, Shinshu University, Nagano; Japan.

[147]Department Physik, Universität Siegen, Siegen; Germany.
[148]Department of Physics, Simon Fraser University, Burnaby BC; Canada.
[149]SLAC National Accelerator Laboratory, Stanford CA; United States of America.
[150]Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
[151]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
[152]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[153]School of Physics, University of Sydney, Sydney; Australia.
[154]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[155(a)]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;[(b)]High Energy Physics Institute, Tbilisi State University, Tbilisi;[(c)]University of Georgia, Tbilisi; Georgia.
[156]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[157]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[158]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[159]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
[160]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
[161]Department of Physics, University of Toronto, Toronto ON; Canada.
[162(a)]TRIUMF, Vancouver BC;[(b)]Department of Physics and Astronomy, York University, Toronto ON; Canada.
[163]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
[164]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
[165]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
[166]University of West Attica, Athens; Greece.
[167]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
[168]Department of Physics, University of Illinois, Urbana IL; United States of America.
[169]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
[170]Department of Physics, University of British Columbia, Vancouver BC; Canada.
[171]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[172]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
[173]Department of Physics, University of Warwick, Coventry; United Kingdom.
[174]Waseda University, Tokyo; Japan.
[175]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
[176]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[177]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[178]Department of Physics, Yale University, New Haven CT; United States of America.
[179]Yerevan Physics Institute, Yerevan; Armenia.
[a] Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[d] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[e] Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP); Portugal.
[f] Also at CERN, Geneva; Switzerland.

[g] Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC); Azerbaijan.
[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Mathematical Sciences, University of South Africa, Johannesburg; South Africa.
[l] Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.
[m] Also at Department of Physics, Bolu Abant Izzet Baysal University, Bolu; Türkiye.
[n] Also at Department of Physics, King's College London, London; United Kingdom.
[o] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[p] Also at Department of Physics, Stellenbosch University; South Africa.
[q] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[r] Also at Department of Physics, University of Thessaly; Greece.
[s] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[t] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
[u] Also at Faculty of Physics, University of Bucharest ; Romania.
[v] Also at Hellenic Open University, Patras; Greece.
[w] Also at Henan University; China.
[x] Also at Imam Mohammad Ibn Saud Islamic University; Saudi Arabia.
[y] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[z] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[aa] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[ab] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[ac] Also at Institute of Particle Physics (IPP); Canada.
[ad] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
[ae] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[af] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ag] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ah] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ai] Also at TRIUMF, Vancouver BC; Canada.
[aj] Also at Università di Napoli Parthenope, Napoli; Italy.
[ak] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[al] Also at University of Sienna; Italy.
[am] Also at Washington College, Chestertown, MD; United States of America.
[an] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased