XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2019)

Highlights from the ATLAS experiment

Martin Spousta, on behalf of the ATLAS Collaboration

*Faculty of Mathematics and Physics, Charles University
V Holešovičkách 2, Prague 180 00, Czech Republic*

Abstract

The ATLAS experiment at the LHC has undertaken an extensive program to probe and characterize the hot and dense quark-gluon plasma created in relativistic heavy ion collisions and, in general, to study non-perturbative and collective properties of the strong interaction. In this report we summarize the most recent results on the collectivity in pp , $p+Pb$ and nucleus-nucleus collisions, results on jets, quarkonia, heavy flavor and electroweak boson production, measured in Pb+Pb and $p+Pb$ collisions. This report covers also new results on electromagnetic processes studied in ultra-peripheral collisions.

Keywords: Heavy-ion collisions, ATLAS, LHC, collectivity in hadronic collisions, azimuthal anisotropies, correlations and fluctuations, ridge, jets, electroweak boson production, quarkonium production, heavy-flavor production, ultra-peripheral collisions, photoproduction, light-by-light scattering

1. Introduction

The ATLAS experiment [1] at the LHC has undertaken an extensive program to probe and characterize the hot and dense quark-gluon plasma (QGP) created in relativistic heavy ion collisions and, in general, to study non-perturbative and collective properties of the strong interaction. During LHC Run 2, several runs dedicated to heavy-ion physics were performed. The collision data that are used in studies by ATLAS, along with information on the total integrated luminosity, is summarized in Table 1.

Section 2 of this report summarizes the latest results on the collectivity in pp , $p+Pb$ and nucleus-nucleus collisions. Section 3 covers results on penetrating probes of QGP in Pb+Pb collisions, namely new results on jets and quarkonia suppression. Section 4 summarizes results on physics of initial state and nuclear geometry, namely new results on electroweak boson production in Pb+Pb collisions and photon and jet production in $p+Pb$ collisions. Section 5 covers new results on the light-by-light scattering and the results on the electromagnetic production of muons which may be used also as penetrating probes of QGP. Unless otherwise stated, by pp , $p+Pb$, and Pb+Pb collisions we mean these collisions at the centre-of-mass energy of 5.02 TeV per colliding nucleon pair.

Email address: martin.spousta@mff.cuni.cz (Martin Spousta, on behalf of the ATLAS Collaboration)

System	Year	$\sqrt{s_{NN}}$ [TeV]	L_{int}
pp	2015 + 2017	5.02	$28 \text{ pb}^{-1} + 0.26 \text{ fb}^{-1}$
Pb+Pb	2015 + 2018	5.02	$0.49 \text{ nb}^{-1} + 1.72 \text{ nb}^{-1}$
p +Pb	2016	5.02	0.4 nb^{-1}
p +Pb	2016	8.16	165 nb^{-1}
pp	2017 + 2018	13	$150 \text{ pb}^{-1} + 193 \text{ pb}^{-1}$
Xe+Xe	2017	5.44	$3 \mu\text{b}^{-1}$

Table 1. Summary of LHC Run 2 datasets used by the ATLAS experiment. For each colliding system, the years of data-taking, along with the centre-of-mass energy per colliding nucleon and total integrated luminosity are provided.

2. Collectivity in pp , p +Pb and nucleus-nucleus collisions

Presence of significant azimuthal anisotropy, also known as flow phenomenon, in nucleus-nucleus collisions is one of the most important arguments for the presence of a hot and dense QGP in those collisions. While the azimuthal anisotropies were measured in great details at many energies and over several collision systems both at the LHC and RHIC, there are still open questions left to be addressed: What is the origin of the flow in “small systems” such as pp or p +Pb? Is there some universality in the flow phenomenon across collision systems? What is the role of geometry and the initial state and its fluctuations? What is the source of the flow of heavy quarks? What is the origin of the flow at high transverse momenta? In this section we discuss the latest results by ATLAS which may help to find answers to these questions.

The azimuthal anisotropy in nucleus-nucleus collisions was quantified in details by measuring flow harmonics $v_2 - v_7$ and $v_2 - v_6$ in Pb+Pb and Xe+Xe collisions, respectively [2, 3]. Significant v_2 is observed up to transverse momentum (p_T) of 60 GeV in Pb+Pb collisions. Compared to Pb+Pb collisions, the Xe+Xe v_2 is larger in the most central collisions. This can be attributed to larger fluctuations in Xe+Xe and a possible deformation of the Xe nucleus, which leads to larger eccentricity in Xe+Xe than in Pb+Pb. For mid-central and peripheral events, the v_2 in Xe+Xe becomes smaller than in Pb+Pb, indicating the increased role of viscous effects. These trends are also observed for the higher-order harmonics and were predicted qualitatively by relativistic viscous hydrodynamics.

Two types of scaling behavior are observed for flow both in Pb+Pb and Xe+Xe collisions. The first scaling is that the v_n for fixed n have the same shape as a function of p_T across different centralities, up to an overall normalization and scaling along the p_T axis [4]. The second scaling is that the ratio $v_n/v_m^{n/m}$ for two harmonics of order m and n is independent of p_T in a given centrality interval [5, 6]. Neither scaling is understood quantitatively. Besides a similarity captured by the scaling behavior there are also differences pointing to a role of fluctuations. One of them is the ordering of flow coefficients in ultra-central (0 – 5%) collisions: $v_3 > v_4 > v_2 \sim v_5$ for p_T above 1 GeV. Another is a weak centrality dependence of higher-order flow harmonics (v_n with $n \geq 3$). To better quantify the role of fluctuations, longitudinal flow decorrelations were measured in Pb+Pb and Xe+Xe collisions [7]. The decorrelation signal increases approximately linearly as a function of the η separation between the two particles. The decorrelation was seen to be larger (smaller) for v_2 (v_3) in Xe+Xe compared to Pb+Pb. While hydrodynamic models are found to describe the ratios of inclusive v_n between Xe+Xe and Pb+Pb, they fail to describe many of the magnitudes and trends in the longitudinal decorrelations between Xe+Xe and Pb+Pb. This suggests that models tuned to describe the transverse dynamics may not necessarily describe the longitudinal structure of the initial state geometry. The new measurements may be used to improve the three-dimensional initial conditions for hydrodynamic models.

Event-by-event fluctuations of flow and correlations between flow harmonics were further studied in Pb+Pb collisions [9] and in 13 TeV pp , 5.02 TeV p +Pb, and 2.76 TeV Pb+Pb collisions [10] using symmetric and asymmetric subevent cumulants. These measurements revealed e.g. signs of significant non-Gaussian fluctuations in v_2 and v_3 in ultra-central Pb+Pb collisions, or a negative correlation between v_2 and v_3 and a positive correlation between v_2 and v_4 which is present for all studied collision systems. While the correlations among flow magnitudes are universal across collision systems, their magnitudes depend on the event multiplicity and the choice of the p_T range and the collision system which provides a clear

Fig. 1. Comparisons of the v_2 measured in different collision systems and collision energies as a function of the measured multiplicity, N_{ch}^{rec} . The v_2 values are obtained with the template-fit method. For the Pb+Pb and Xe+Xe measurements, the peripheral reference in the template fits is constructed using pp collisions at 5.02 TeV that have $N_{ch}^{rec} < 20$. For all other systems, the peripheral reference is constructed using events from the corresponding collision system that have $N_{ch}^{rec} < 20$. The plots are for $0.5 \text{ GeV} < p_T < 5 \text{ GeV}$. The error bars and bands represent statistical and systematic uncertainties, respectively, and are typically too small to be observed. Results taken from Ref. [8].

discriminative power for modeling the origin of flow in small collision systems.

The origin of flow in small collision systems may be better understood also using results from several other measurements. This first one is the measurement of the correlation between the flow harmonics ($v_2 - v_4$) and the mean p_T in p +Pb and Pb+Pb collisions [11]. The magnitude of this correlation is quantified by modified Pearson correlation coefficient. A strong positive correlation is observed between v_2 and mean p_T in mid-central and central collisions while an anticorrelation is seen for peripheral events. An anticorrelation is observed also for p +Pb collisions, but exhibiting different trends compared to peripheral Pb+Pb (a growth of the correlation with number of charged particles in the event (N_{ch}) is seen in Pb+Pb, but no N_{ch} dependence is seen in p +Pb). One of the clear next steps to disentangle the origin of these correlations is to measure these correlations in pp collisions.

The second measurement is the measurement of elliptic flow of muons from the decay of charm and bottom hadrons in 13 TeV pp collisions [12]. A significant non-zero v_2 is observed for muons from charm decays, while the v_2 value for muons from bottom decays is observed to be consistent with zero. This indicates that the collectivity in small collision systems does not persist up to the scale of heavy quark masses. This measurement can be compared to the measurement of the same quantities in Pb+Pb collisions [13]. In the case of Pb+Pb, the v_2 and v_3 for muons from bottom decays are seen to be non-zero (but significantly smaller than the v_2 and v_3 for charm muons). The Pb+Pb results can significantly discriminate between models of heavy-quark energy loss and constrain heavy-quark transport coefficients in the QGP.

The third measurement to help understanding the flow in small systems is a measurement of v_2 in ultra-peripheral Pb+Pb collisions [14]. Significant v_2 values of 4–6% are observed in these photo-nuclear events. The v_2 values have a similar dependence on p_T and N_{ch} as in 13 TeV pp and 5.02 TeV p +Pb collisions, but an overall smaller magnitude. The signal of v_2 in photo-nuclear events may be understood in the vector-meson dominance picture as arising from a ρ +Pb or ω +Pb interaction at a lower energy than the equivalent nucleon-nucleon collision energy.

The last measurements to be mentioned in the context of small systems is the measurement of ridge in Z-triggered events in 13 TeV and 8 TeV pp collisions [15]. A significant pile-up contribution to the two-particle correlations is subtracted using a new pile-up correction method. The magnitude of the observed v_2 as a function of multiplicity and p_T is found to be consistent with that observed in inclusive pp collisions. This measurement demonstrates that in pp collisions, the long-range correlation involving soft particles is not significantly altered by the presence of a hard-scattering process.

It is also important to study the high- p_T limit of flow in small collision system. Such a study was done in 8.16 TeV p +Pb collisions [16]. The measurement was performed using minimum-bias events and events

Fig. 2. Compilation of results for the nuclear modification factor R_{AA} vs. p_T or $m_{W/Z}$ in different channels from the Run 2 Pb+Pb and pp data. *Left*: Results for Z bosons (black plus, plotted at the Z boson mass), $W^\pm$ bosons (orange cross, plotted at the W boson mass), anti- k_t $R = 0.4$ jets (red circles), charged hadrons (blue diamonds), prompt J/Ψ 's (green stars), and $\Upsilon(1S)$ particles (purple squares). *Right*: Results for anti- k_t $R = 0.4$ jets (red circles), charged hadrons (blue diamonds), prompt J/Ψ 's (green stars), non-prompt J/Ψ 's (orange pluses), and $\Upsilon(1S)$ particles (purple squares). In both panels, the statistical uncertainties are shown as vertical bars and the total systematic uncertainties, including pp luminosity and T_{AA} uncertainties, are shown as boxes. Results taken from Ref. [8].

triggered by jets. The anisotropies for particles with p_T of 0.5–2 GeV are consistent between minimum bias (MB) events and jet-triggered events and also consistent with trends predicted by relativistic hydrodynamics. In the p_T range of 2–9 GeV, the anisotropies are larger in MB events than in jet-triggered events which might be a result of changing admixture of particles from hard scattering and the underlying event. For p_T above 9 GeV, the v_n results are again consistent between MB and jet-triggered events. The v_2 plateaus at a value of 0.025 up to a p_T of 50 GeV. This result cannot be explained in the theoretical context of jet quenching or “eremitic” expansion calculations while simultaneously describing the observed lack of suppression of high- p_T hadron and jet yields in p +Pb collisions.

Figure 1 presents a summary of selected results on flow in small systems.

3. Penetrating probes of QGP in Pb+Pb collisions

Significant modifications of the internal structure of jets in central Pb+Pb collisions compared to peripheral collisions or pp collisions were established at ATLAS by measurements of inclusive jet fragmentation functions [17, 18, 19]. Yield of hadrons with $p_T < 4$ GeV is enhanced, yield of hadrons with $p_T = 4$ –20 GeV is suppressed, and yield of hadrons with $p_T > 20$ GeV is seen to be enhanced in Pb+Pb with respect to pp collisions. ATLAS has now extended these measurements to study jet fragmentation in boson-triggered systems and to measure the radial dependence of fragmentation functions.

Fragmentation functions as a function of the radial distance from the jet axis (r) were measured in Pb+Pb and pp collisions extending up to $r = 0.8$. A broadening of jets for low- p_T particles ($p_T < 4$ GeV) and a narrowing of jets for high- p_T particles ($p_T > 4$ GeV) is seen, at the same time the core of the jet ($r < 0.05$) remains almost unmodified. This may help to qualitatively constrain the role of the wide-angle radiation, medium back-reaction to the propagating parton, or a role of the flavor of the initial parton.

Internal structure of jets was also measured for jets from γ -jet systems [20]. While in the 30–80% centrality bin the Pb+Pb-to- pp ratios of fragmentation functions are measured to be consistent between the inclusive and γ -tagged jets, a difference between the inclusive and γ -tagged jets is seen for the 0–30% centrality bin. The minimum of the ratio is significantly shifted toward higher p_T of hadrons and the magnitude of the low- p_T enhancement is also larger. These fully particle-level corrected results along with results from measurements of photon-jet transverse momentum correlations [21] may allow further constraints to be put on the models of the energy loss.

It is not simple to extend the measurements of jet fragmentation with fully reconstructed jets to the kinematic region of jets with p_T of a few tens of GeV (e.g. due to inefficiencies which may be different

for quenched and non-quenched jets). The alternative, allowing to go lower in p_T , is a measurement of conditional yields of charged particles. The measurement of charged particle yields in Z -tagged events was performed in Pb+Pb and pp collisions [22]. The integrated yield was measured over $|\Delta\phi| > 3/4\pi$ from the Z boson direction and the Pb+Pb-to- pp ratio, I_{AA} , of this yield was evaluated. The I_{AA} exhibits similar trends as those seen in fragmentation functions but with an overall larger amplitude of the modification which might be due to the fact that I_{AA} is a result of combination of the jet suppression with modified fragmentation. It might also reflect larger modifications of jets at lower p_T .

To further improve on the understanding of the modifications of jet internal structure, ATLAS measured the nuclear modification factor, R_{AA} , of jets for large-radius jets. The large-radius jets are reconstructed with the anti- k_t algorithm using a radius parameter of $R = 1.0$, by re-clustering anti- k_t $R = 0.2$ jets with $p_T > 35$ GeV [23]. After applying a trimming procedure, the large-radius jet constituents are re-clustered using the k_t algorithm in order to obtain the splitting parameter, $\sqrt{d_{12}}$, which characterizes the transverse momentum scale for the hardest splitting in the jet. The inclusive jet R_{AA} is qualitatively similar to the previously measured R_{AA} of $R = 0.4$ jets [24] confirming a presence of sizable jet quenching at a scale of 1 TeV. When measured as a function of $\sqrt{d_{12}}$, a significant evolution of R_{AA} is observed. The R_{AA} values for jets with small $\sqrt{d_{12}}$ (corresponding to jets with just one single subjet) were found to be significantly larger compared to the R_{AA} for other $\sqrt{d_{12}}$ values (that is those having a more complex substructure).

It is not only jets or inclusive charged particles which are measured to be strongly suppressed in Pb+Pb collisions. Figure 2 presents a summary of selected suppression measurements for various final states. New results of the measurement of Υ production [25] quantify the R_{AA} of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(2S + 3S)$ states. An expected ordering of the suppression reflecting the binding energy of Υ states is seen: $R_{AA}[\Upsilon(1S)] > R_{AA}[\Upsilon(2S)] > R_{AA}[\Upsilon(2S + 3S)]$. No significant p_T and rapidity dependence of the suppression is seen. All the suppression measurements presented here should be checked against effects from the initial geometry of the collision and modifications of parton distribution functions in the environment of the nucleus. This may be done based on the measurements presented in the next section.

4. Physics of initial state and nuclear geometry

Electroweak bosons production in Pb+Pb collisions may be considered to be standard candles for suppression measurements presented in the previous section. ATLAS have measured Z and W boson production [26, 27] in Pb+Pb collisions in the electron and muon decay channels. The measurements in Pb+Pb collisions are compared with those made in pp collisions [28] and the R_{AA} is calculated. The results are then compared with predictions obtained at next-to-leading order (NLO) using nucleon and nuclear parton distribution functions (nPDFs). The R_{AA} of Z is found to be consistent with unity for all centrality intervals. The nuclear modification factor measured as a function of rapidity agrees with unity and is consistent with an NLO QCD calculation including the isospin effect. The R_{AA} of W bosons is also found to be consistent with theoretical predictions. No dependence of normalized W yields on centrality and a good agreement with predictions are observed for mid-central and central collisions. For peripheral collisions, the data agree with predictions within 1.7 (0.9) standard deviations for W^- (W^+) bosons. The trend observed in the R_{AA} for peripheral collisions goes in the opposite direction to predictions including the centrality bias evaluated with the HG-PYTHIA model [29] for charged-hadron production measured previously by ALICE [30]. New precision measurements of W and Z bosons production in Pb+Pb collisions have confirmed the expected smallness of nPDF effects in the studied kinematic region and provide new constraints on these effects.

Initial state effects are further studied in two p +Pb measurements. The first one is the measurement of inclusive production of prompt, isolated photons in p +Pb collisions at 8.16 TeV [31]. A measurement of the nuclear modification factor is done for photons with transverse energies in the region of 25 – 550 GeV using a NLO pQCD-based extrapolation of previously published pp data at $\sqrt{s} = 8$ TeV. The data are compatible with the expectation that the parton distribution functions are modestly modified in nuclei in this kinematic region and may help to place an upper limit on the possible amount of energy lost by partons in the initial stages of nuclear collisions.

The second p +Pb measurement is the measurement of forward-forward and forward-central dijet azimuthal angular correlations and conditional yields in pp and p +Pb collisions [32] (the forward rapidity

interval is $2.7 < y < 4.0$). These measurements probe the nuclear gluon density in regions of small parton momentum fractions (x) where gluon saturation may play a role. No significant broadening of azimuthal angular correlations is observed for forward-forward or forward-central dijets in p +Pb compared to pp collisions. For forward-forward jet pairs in the proton-going direction, the ratio of conditional yields in p +Pb collisions to those in pp collisions is suppressed by approximately 20%, with no significant dependence on the p_T of the dijet system. No modification of conditional yields is observed for forward-central dijets. The suppression seen in the data may be used to constrain possible nuclear effects including saturation.

5. Ultra-peripheral collisions

Boosted proton and nuclei are sources of significant electromagnetic (EM) fields. These EM fields can be treated as a beam of quasi-real photons with a small virtuality of $Q^2 < 1/R^2$, where R is the radius of the charge distribution ($Q^2 < 10^{-3} \text{ GeV}^2$ for lead ions). In ultra-peripheral collision (UPC) events, with impact parameters larger than twice the radius of the nuclei, the strong interaction does not play a role and the only interaction comes from EM fields.

Since the photon flux associated with each nucleus scales as Z^2 , the cross section for photon induced processes is extremely enhanced as compared to pp collisions. One of interesting processes that may be studied in this configuration is the light-by-light scattering. This first strong evidence for that process was reported by ATLAS in 2017 [33] with a significance of 4.4σ . New measurement of the light-by-light scattering using 2018 Pb+Pb data [34] brought an observation of this process at the level of 8.2σ and also lowered the kinematic thresholds. In the new measurement, candidates are selected in events with two photons produced exclusively, each with transverse energy, $E_T > 3 \text{ GeV}$, diphoton invariant mass, $m_{\gamma\gamma} > 6 \text{ GeV}$, and small diphoton transverse momentum and acoplanarity. After applying all selection criteria, 59 candidate events are observed for a background expectation of 12 ± 3 events. Besides being a precision test of QED, the light-by-light scattering may also put limits on production of particles beyond the Standard Model such as axion-like particles, magnetic monopoles, or vector-like fermions [35].

The EM fields are naturally also present in inelastic heavy-ion collisions. Production of muons from the process $\gamma\gamma \rightarrow \mu^+\mu^-$ may bring a new way to study EM degrees of freedom of QGP. This “non-UPC” dimuon production was studied first using 2015 Pb+Pb data [36] and later using 2015+2018 Pb+Pb data [37]. In peripheral collisions, the muons exhibit a strong, expected back-to-back correlation. In central collisions, the angular correlations are observed to be broadened significantly. This is quantified in the original measurement [36] by measuring the acoplanarity distributions (acoplanarity $\alpha = 1 - \Delta\phi/\pi$, where $\Delta\phi$ is the azimuthal angle between muons). With the improved statistical precision of the new measurement [37], an additional depletion is observed in the acoplanarity distributions near $\alpha = 0$. This was further quantified by measuring the $k_\perp = \bar{p}_T|\pi - \Delta\phi|$ (where $\bar{p}_T$ is the average transverse momentum of muons). While the α distributions are observed to vary strongly with $\bar{p}_T$, the distributions of $k_\perp$ are observed to be approximately independent of $\bar{p}_T$ as would be expected if the modification of the distributions results from a mechanism that imparts a momentum to one or both of the muons in the final state or to the photons in the initial state. The $k_\perp$ distributions show a centrality-dependent shift of the most-probable $k_\perp$ value away from $k_\perp = 0$. In the 0 – 5% most central collisions the peak in the $k_\perp$ distribution is shifted by $36 \pm 1 \text{ MeV}$.

6. Conclusions

The ATLAS experiment at the LHC has undertaken an extensive heavy-ion physics program. In this short report we have summarized the latest results on the collectivity in pp , p +Pb and nucleus-nucleus collisions, results on penetrating probes of QGP in Pb+Pb collisions, results on physics of initial state and nuclear geometry, and results on the electromagnetic production in ultra-peripheral collisions. New results by ATLAS should help to answer many open questions in the field. They also open doors to the Run 3 heavy-ion physics summarized in Ref. [38].

Acknowledgment

This work was supported by Grant Agency of the Czech Republic under grant 18-12859Y, by the Ministry of Education, Youth and Sports of the Czech Republic under grant LTT 17018, and by Charles University grant UNCE/SCI/013.

Copyright 2020 CERN for the benefit of the ATLAS Collaboration. CC-BY-NC-ND-4.0 license.

References

- [1] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003. doi:10.1088/1748-0221/3/08/S08003.
- [2] ATLAS Collaboration, Measurement of the azimuthal anisotropy of charged particles produced in $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb collisions with the ATLAS detector, Eur. Phys. J. C78 (12) (2018) 997. arXiv:1808.03951, doi:10.1140/epjc/s10052-018-6468-7.
- [3] ATLAS Collaboration, Measurement of the azimuthal anisotropy of charged-particle production in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV with the ATLAS detector arXiv:1911.04812.
- [4] A. Collaboration, Measurement of long-range pseudorapidity correlations and azimuthal harmonics in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector, Phys. Rev. C90 (4) (2014) 044906. arXiv:1409.1792, doi:10.1103/PhysRevC.90.044906.
- [5] S. Collaboration, Azimuthal anisotropy at RHIC: The First and fourth harmonics, Phys. Rev. Lett. 92 (2004) 062301. arXiv:nuclex/0310029, doi:10.1103/PhysRevLett.92.062301.
- [6] A. Collaboration, Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector, Phys. Rev. C86 (2012) 014907. arXiv:1203.3087, doi:10.1103/PhysRevC.86.014907.
- [7] ATLAS Collaboration, Longitudinal flow decorrelations in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV with the ATLAS detector, ATLAS-CONF-2019-055.
- [8] ATLAS Collaboration, Compilation plots of Run 2 Heavy Ions results for Quark Matter 2019, ATLAS-PUB-2020-003.
- [9] ATLAS Collaboration, Fluctuations of anisotropic flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, Submitted to: JHEParXiv:1904.04808.
- [10] 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. B789 (2019) 444–471. arXiv:1807.02012, doi:10.1016/j.physletb.2018.11.065.
- [11] ATLAS Collaboration, Measurement of flow harmonics correlations with mean transverse momentum in lead-lead and proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector arXiv:1907.05176.
- [12] ATLAS Collaboration, Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector arXiv:1909.01650.
- [13] ATLAS Collaboration, Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, ATLAS-CONF-2019-053.
- [14] ATLAS Collaboration, Two-particle azimuthal correlations in photo-nuclear ultra-peripheral Pb+Pb collisions at 5.02 TeV with ATLAS, ATLAS-CONF-2019-022.
- [15] ATLAS Collaboration, Measurement of long-range two-particle azimuthal correlations in Z-boson tagged pp collisions at $\sqrt{s}=8$ and 13 TeV arXiv:1906.08290.
- [16] ATLAS Collaboration, Transverse momentum and process dependent azimuthal anisotropies in $\sqrt{s_{NN}} = 8.16$ TeV p +Pb collisions with the ATLAS detector arXiv:1910.13978.
- [17] ATLAS Collaboration, Measurement of inclusive jet charged-particle fragmentation functions in Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV with the ATLAS detector, Phys. Lett. B739 (2014) 320–342. arXiv:1406.2979, doi:10.1016/j.physletb.2014.10.065.
- [18] ATLAS Collaboration, Measurement of jet fragmentation in Pb+Pb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, Eur. Phys. J. C77 (6) (2017) 379. arXiv:1702.00674, doi:10.1140/epjc/s10052-017-4915-5.
- [19] ATLAS Collaboration, Measurement of jet fragmentation in Pb+Pb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, Phys. Rev. C98 (2) (2018) 024908. arXiv:1805.05424, doi:10.1103/PhysRevC.98.024908.
- [20] ATLAS Collaboration, Comparison of Fragmentation Functions for Jets Dominated by Light Quarks and Gluons from pp and Pb+Pb Collisions in ATLAS, Phys. Rev. Lett. 123 (4) (2019) 042001. arXiv:1902.10007, doi:10.1103/PhysRevLett.123.042001.
- [21] ATLAS Collaboration, Measurement of photon-jet transverse momentum correlations in 5.02 TeV Pb+Pb and pp collisions with ATLAS, Phys. Lett. B789 (2019) 167–190. arXiv:1809.07280, doi:10.1016/j.physletb.2018.12.023.
- [22] ATLAS Collaboration, Measurement of Z-tagged charged-particle yields in 5.02 TeV Pb+Pb and pp collisions with the ATLAS detector, ATLAS-CONF-2019-052.
- [23] ATLAS Collaboration, Measurement of suppression of large-radius jets and its dependence on substructure in Pb+Pb at 5.02 TeV by ATLAS detector, ATLAS-CONF-2019-056.
- [24] ATLAS Collaboration, Measurement of the nuclear modification factor for inclusive jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, Phys. Lett. B790 (2019) 108–128. arXiv:1805.05635, doi:10.1016/j.physletb.2018.10.076.
- [25] ATLAS Collaboration, Production of $\Upsilon(nS)$ mesons in Pb+Pb and pp collisions at 5.02 TeV with ATLAS, ATLAS-CONF-2019-054.
- [26] ATLAS Collaboration, Z boson production in Pb+Pb collisions at $\sqrt{s_{NN}}= 5.02$ TeV measured by the ATLAS experimentalXiv:1910.13396.

- [27] ATLAS Collaboration, Measurement of $W^\pm$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, Eur. Phys. J. C79 (11) (2019) 935. arXiv:1907.10414, doi:10.1140/epjc/s10052-019-7439-3.
- [28] ATLAS Collaboration, Measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector, Eur. Phys. J. C79 (2) (2019) 128, [Erratum: Eur. Phys. J.C79,no.5,374(2019)]. arXiv:1810.08424, doi:10.1140/epjc/s10052-019-6870-9, 10.1140/epjc/s10052-019-6622-x.
- [29] C. Loizides, A. Morsch, Absence of jet quenching in peripheral nucleus-nucleus collisions, Phys. Lett. B773 (2017) 408–411. arXiv:1705.08856, doi:10.1016/j.physletb.2017.09.002.
- [30] ALICE Collaboration, Analysis of the apparent nuclear modification in peripheral Pb-Pb collisions at 5.02 TeV, Phys. Lett. B793 (2019) 420–432. arXiv:1805.05212, doi:10.1016/j.physletb.2019.04.047.
- [31] ATLAS Collaboration, Measurement of prompt photon production in $\sqrt{s_{NN}} = 8.16$ TeV p +Pb collisions with ATLAS, Phys. Lett. B796 (2019) 230–252. arXiv:1903.02209, doi:10.1016/j.physletb.2019.07.031.
- [32] ATLAS Collaboration, Dijet azimuthal correlations and conditional yields in pp and p +Pb collisions at $s_{NN}=5.02$ TeV with the ATLAS detector, Phys. Rev. C100 (3) (2019) 034903. arXiv:1901.10440, doi:10.1103/PhysRevC.100.034903.
- [33] ATLAS Collaboration, Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC, Nature Phys. 13 (9) (2017) 852–858. arXiv:1702.01625, doi:10.1038/nphys4208.
- [34] ATLAS Collaboration, Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector, Phys. Rev. Lett. 123 (5) (2019) 052001. arXiv:1904.03536, doi:10.1103/PhysRevLett.123.052001.
- [35] ATLAS Collaboration, Prospects for Measurements of Photon-Induced Processes in Ultra-Peripheral Collisions of Heavy Ions with the ATLAS Detector in the LHC Runs 3 and 4, ATL-PHYS-PUB-2018-018.
- [36] ATLAS Collaboration, Observation of centrality-dependent acoplanarity for muon pairs produced via two-photon scattering in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, Phys. Rev. Lett. 121 (21) (2018) 212301. arXiv:1806.08708, doi:10.1103/PhysRevLett.121.212301.
- [37] ATLAS Collaboration, Measurement of non-exclusive dimuon pairs produced via $\gamma\gamma$ scattering in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector, ATLAS-CONF-2019-051.
- [38] Z. Citron, et al., Report from Working Group 5 arXiv:1812.06772, doi:10.23731/CYRM-2019-007.1159.