Overview of ATLAS results

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Abstract

The heavy-ion programme in the ATLAS experiment at the Large Hadron Collider aims to probe and characterise hot and dense matter created in relativistic lead-lead collisions. Moreover, smaller collision systems involving nuclei and hadrons are of interest to disentangle initial- from final-state effects. This report presents new results based on lead-lead and proton-proton data collected at $\sqrt{s_{NN}} = 5.02$ TeV in 2015, including measurements of bulk collectivity, charged-particle production, electroweak bosons, photon-jet correlations, and quarkonium suppression. First attempts to measure electromagnetic processes in ultra-peripheral collisions are also discussed.

Keywords: Quarkonia suppression, Gamma-jet correlations, Light-by-light scattering, Angular correlations

1. Introduction

The Quark-Gluon Plasma (QGP) was first observed in experiments at RHIC [1, 2, 3, 4] and since then it has been studied in relativistic heavy-ion collisions. Significantly higher collision energies available at the LHC as compared to RHIC, result in increased volume, lifetime and temperature of the QGP.

The LHC provided lead-lead (Pb+Pb) collisions at $\sqrt{s_{NN}} = 2.76$ TeV in years 2010-2013 (so-called Run 1) and at $\sqrt{s_{NN}} = 5.02$ TeV in Run 2 which commenced in 2015 after a technical break. In addition to the Pb+Pb system, proton-lead (p +Pb) and proton-proton (pp) collisions are of interest for the heavy-ion measurements. They serve as reference systems to disentangle initial- from final-state effects. The ATLAS experiment [5] collected p +Pb data at $\sqrt{s_{NN}} = 5.02$ TeV in 2013 while pp collisions at the same center-of-mass energy were provided prior to the Pb+Pb data taking in 2015.

In the heavy-ion programme at ATLAS two major areas can be identified. A soft sector in which the analyses aim at elucidating long-wavelength properties of the system using tools such as angular correlations. On the other hand, the measurements in the hard sector result in a better understanding of short-range interactions which in turn can be utilised to probe properties of the

QGP. Typical measurements are quenching/suppression of various hard probes.

The ATLAS Collaboration extensively studied various observables at lower Run 1 energy. In this report selected results from the aforementioned two sectors will be presented based on Pb+Pb and pp data samples collected at higher center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV in 2015. In addition, at conditions available in Pb+Pb collisions in Run 2 a measurement of light-by-light scattering can be attempted for the first time. Its results will be discussed as well.

2. Quarkonia production

ATLAS has reported on measurements of prompt and non-prompt differential production cross sections and nuclear modification factors of the J/ψ and $\psi(2S)$ mesons [6]. The measurements are performed in the dimuon decay channel in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, with an integrated luminosity of 0.49 nb^{-1} , and in pp collisions at $\sqrt{s} = 5.02$ TeV, with an integrated luminosity of 25 pb^{-1} . The measurements are presented for $9 < p_T < 40$ GeV in transverse momentum, and $|y| < 2.0$ in rapidity.

The suppression of charmonium states is quantified

by the nuclear modification factor, R_{AA} , which can be defined for a given centrality class as:

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma^{pp}}, \quad (1)$$

where N_{AA} is the per-event yield of charmonium states measured in Pb+Pb collisions, $\langle T_{AA} \rangle$ is the mean nuclear thickness function and σ^{pp} is the cross section for the production of the corresponding charmonium states in pp collisions at the same energy.

A strong suppression of both prompt and non-prompt J/ψ and $\psi(2S)$ mesons is found. The maximal suppression of both prompt and non-prompt J/ψ is observed for the most central events. The distribution of the dependence of R_{AA} on centrality is approximately the same for both prompt and non-prompt J/ψ . The similarity of this shape for both prompt and non-prompt J/ψ is striking since in the simplest interpretation the observed prompt mesons come predominantly from potentially fragile composite systems exposed to the hot dense medium while the non-prompt mesons come predominantly from b -quarks traversing through the medium; thus, one might expect different trends as a function of centrality.

Figures 1 and 2 show ratios of R_{AA} of $\psi(2S)$ to J/ψ meson production as a function of the number of participants, N_{part} , for both prompt and non-prompt components, respectively. Values consistent with unity are measured for the non-prompt mesons, while the values observed for the prompt mesons are below unity. This result is consistent with what would be expected for b -quarks in the hot dense medium with the same behaviour for both mesons, while composite mesons formed in the hot and dense medium are affected differently. In particular, the $\psi(2S)$ meson is suppressed more than the J/ψ meson, a pattern consistent with the lower binding energy of the $\psi(2S)$ meson causing it to have a lower formation and survival probability in the QGP for the values of $p_T^{\psi(nS)}$ sampled in this measurement.

3. Photon-jet correlations

ATLAS has presented a study of photon-jet angular and momentum correlations in $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb and pp events with photons with transverse momenta of $60 < p_T^\gamma < 200$ GeV [7]. The data are statistically corrected for the presence of combinatoric photon-jet pairs and of dijet pairs where one of the jets has been misidentified as a photon. The measured quantities in data are compared to the analogous quantities in simulated photon-jet events overlaid with minimum-bias

Figure 1: Ratio of R_{AA} for $\psi(2S)$ to J/ψ as a function of centrality expressed as N_{part} , for prompt meson production [6]. The narrow error bar represents the statistical uncertainties while the wider error bar represents the total systematic uncertainty.

Figure 2: Ratio of R_{AA} for $\psi(2S)$ to J/ψ as a function of centrality expressed as N_{part} , for non-prompt meson production [6]. The narrow error bar represents the statistical uncertainties while the wider error bar represents the total systematic uncertainty.

Pb+Pb events. The per-photon distributions of the jet-photon p_T balance, $x_{J\gamma} = p_T^{\text{jet}}/p_T^\gamma$, for pairs with a back-to-back configuration, $\Delta\phi > 7\pi/8$, are observed to have a significantly modified total yield and shape in central Pb+Pb collisions. Figure 3 compares the distributions in 0-10% Pb+Pb events to the simulated PYTHIA8 photon-jet events overlaid with minimum-bias Pb+Pb data. In each p_T^γ selection, the distributions in data are substantially modified with respect to the results of the simulation, in a manner that is consistent with a shift to lower values of $x_{J\gamma}$. The distributions have a different shape (they do not exhibit a clear peak within the visible $x_{J\gamma}$

range), and the integrated yield of associated jets above the minimum $x_{J\gamma}$ value is suppressed. This pattern of modification is indicative of a picture of parton-energy loss in the hot and dense medium.

These modifications are systematic in collision centrality and p_T^γ , consistent with the picture that the partons initially produced opposite to a high- p_T photon lose energy in their interactions with the QGP but remain angularly well-correlated with the photon direction.

Figure 3: Measured distributions of the jet-to-photon transverse momentum ratio $x_{J\gamma}$ in 0-10% Pb+Pb collisions (filled circles), pp collisions (open squares) and PYTHIA8 simulation overlaid with 0-10% Pb+Pb data (yellow histogram) [7]. Each panel shows a different p_T^γ selection.

4. Particle production in the p +Pb system

Charged-particle spectra

In Run 1 LHC collaborations performed measurements of inclusive charged particle production [9, 10] that in extreme cases showed an enhancement of approximately 30% with respect to unity in R_{pPb} for particles with $p_T > 20$ GeV. All these measurements used a reference which was derived by interpolating between pp data taken at other $\sqrt{s}$ as no reference data were available at $\sqrt{s} = 5.02$ TeV at that time.

With the advent of Run 2, a large sample of pp collisions at $\sqrt{s} = 5.02$ TeV was provided by the LHC enabling the study of inclusive charged-particle production in pp collisions. ATLAS has measured charged-particle spectra in the pp system at $\sqrt{s} = 5.02$ TeV using an integrated luminosity of 25 pb^{-1} . Then a nuclear modification factor, R_{pPb} , is extracted from charged-particle spectra measured for p +Pb collisions in Ref. [10] for a very wide range of transverse momentum $4 < p_T < 189$ GeV and rapidity $-2.0 < y < 1.5$.

Figure 4 shows R_{pPb} in the 0-90% centrality interval. The p_T dependence is substantially reduced compared to the previous estimate from ATLAS that relied upon interpolation. No significant deviation from unity is observed in the centrality interval 0-90% for any transverse momentum.

Figure 4: Nuclear modification factor R_{pPb} for charged particles measured in the 0-90% centrality interval [8]. Statistical uncertainties are shown with vertical lines and brackets represent systematic uncertainties, with the exception of the fully correlated systematic uncertainty that is shown with the gray band around unity.

Z boson production

The ATLAS collaboration has studied Z boson production in the dimuon channel in pp collisions at $\sqrt{s} = 5.02$ TeV using $24.7 \pm 1.3 \text{ pb}^{-1}$ of integrated luminosity collected in 2015. Within $|y^Z| < 2.5$, and $66 < m_{\ell\ell} < 116$ GeV, a total of 7293 Z boson candidates are reconstructed in the $Z \rightarrow \mu^+\mu^-$ channels. The measured integrated cross section is $590 \pm 9 \text{ (stat.)} \pm 12 \text{ (syst.)} \pm 32 \text{ (lumi.) pb}$, consistent with the NNLO prediction using the CT14 parton distribution functions (PDF) of $573.77 \pm_{-15.96}^{+13.94} \text{ pb}$. The rapidity differential cross section is studied, and it is also in good agreement with pQCD calculations. The results are used to confront the nuclear modification factor of the previously measured Z boson cross section in p +Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [12] which is shown as a function of y^Z in Figure 5. The rapidity is defined such that the proton travels forward in the positive direction and the lead ion travels backwards in the negative direction. To calculate the R_{pPb} both positive and negative rapidity values from the y^Z differential p +Pb cross section are divided by the corresponding $|y^Z|$ value measured in the pp collisions. The R_{pPb} shows an asymmetry qualitatively consistent with nuclear modifications of PDF. This asymmetry is more pronounced in central p +Pb collisions compared to peripheral events.

5. Light-by-light scattering

ATLAS has reported an evidence for light-by-light (LbyL) scattering signatures in quasi-real photon interactions occurring in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [13]. The studied data set corresponds to $480 \mu\text{b}^{-1}$. After applying event selection

Figure 5: Nuclear modification factor as a function of Z boson rapidity [11]. The uncertainties on each point include statistical and systematic uncertainties from p +Pb and pp measurements. The band around unity represents the uncertainty of the luminosities. The blue line shows an expected R_{pPb} based on simulation.

Figure 6: Diphoton acoplanarity distribution for events in the LbL signal region [13].

criteria requiring no activity in the detector except for two well reconstructed photons, 13 event are observed, while 7.3 signal events are expected from predictions. The dominant background processes, i.e. central exclusive production $gg \rightarrow \gamma\gamma$, exclusive dilepton production $\gamma\gamma \rightarrow e^+e^-$ as well as other fake-photon backgrounds, are estimated using data-driven methods. After accounting for all of these sources, 2.6 background events are expected, with an uncertainty of 0.7. Figure 6 shows an acoplanarity¹ distribution for the diphoton candidates with $p_T^{\gamma\gamma} < 2$ GeV. A good agreement between a sum of signal plus background contributions and the data is observed. The significance is determined to be 4.4σ . After background subtraction and corrections, the cross section of the $\gamma\gamma \rightarrow \gamma\gamma$ process for photon transverse momentum, $E_T > 3$ GeV, photon pseudorapidity, $|\eta| < 2.4$, invariant mass of the diphoton system, $m^{\gamma\gamma} > 6$ GeV, diphoton transverse momentum, $p_T^{\gamma\gamma} < 2$ GeV and acoplanarity, $A_{co} < 0.01$ is measured to be 70 ± 20 (stat.) ± 17 (syst.) nb, which is compatible with the Standard Model prediction of 49 ± 10 nb [14].

6. Particle correlations

Flow harmonics in Pb+Pb collisions

Azimuthal anisotropy of charged particles in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been measured using Scalar Product (SP), Event Plane (EP) and Two Particle Correlations (2PC) methods [15]. The measurements are done using an integrated luminosity of

¹ Acoplanarity of the diphoton system is defined as $A_{co} = 1 - \frac{\Delta\phi_{\gamma\gamma}}{\pi}$, where $\Delta\phi_{\gamma\gamma}$ is a difference in azimuthal angles of two photons.

$5 \mu\text{b}^{-1}$ in SP/EP and $22 \mu\text{b}^{-1}$ in 2PC results. The azimuthal anisotropies, quantified by the flow harmonics v_n , are measured using the SP ($n = 2 - 7$), EP ($n = 2 - 5$) and 2PC ($n = 1 - 6$) methods. The measurements are done over wide transverse momentum ($0.5 < p_T < 25$ GeV), pseudorapidity ($|\eta| < 2.5$) and centrality (0-80%) ranges. All harmonics show similar p_T -dependence, first increasing with p_T up to a maximum at around 3-4 GeV and then decreasing for higher p_T values. However, significant values of the second order harmonic v_2 persist up to 25 GeV. Figure 7 shows v_n as a function of event centrality for the SP method. The elliptic flow signal is strongly dependent on event centrality and it is largest in mid-central events (50-60%). The higher-order harmonics show a weak centrality dependence, which is consistent with an anisotropy associated with fluctuations in the initial geometry. An inset shows the v_6 and v_7 harmonics with adjusted scale. The latter could be measured for the first time in Pb+Pb collisions.

A hierarchy $v_{n+1} < v_n$ can be observed for harmonics from 3 to 7 for all ranges of p_T and all centralities. The v_n coefficients are found to exhibit only a weak η -dependence across all centrality intervals. The results obtained using the EP and SP methods are consistent for harmonics of order $n \geq 3$. A small, systematic difference is observed for v_2 , where the values obtained from the SP method are up to 3% larger than the values obtained using the EP method. The 2PC and SP methods give values for v_n that are quite consistent up to 10 GeV. However, in the most central events the SP method gives systematically larger values for v_2 for $p_T > 2$ GeV. Comparisons to measurements in Pb+Pb collisions at 2.76 TeV show that the p_T dependence of the v_n shows no change between 2.76 and 5.02 TeV.

Figure 7: Integrated $v_n\{\text{SP}\}$ as a function of centrality integrated over $|\eta| < 2.5$ and $0.5 < p_T < 25$ GeV extracted from the SP method [15]. In the inset the v_6 and v_7 are shown with adjusted scale. Results are averaged over the intervals indicated by horizontal error bars. The vertical error bars indicate statistical uncertainties. The shaded areas indicate systematic uncertainties.

Multi-particle cumulants in pp collisions

Four-particle cumulants have been measured by ATLAS in the pp system at $\sqrt{s} = 5.02$ and 13 TeV [16]. Two analysis methods are applied to calculate $c_2\{4\}$ for particles with transverse momenta of $0.3 < p_T < 3.0$ GeV and $0.5 < p_T < 5.0$ GeV. In Method 1, the cumulants are calculated for events with a fixed $N_{\text{trk}}^{\text{ref}}$ multiplicity in order to avoid event-by-event multiplicity fluctuations. The unit width bins in $N_{\text{trk}}^{\text{ref}}$ are then combined to broader, statistically significant $N_{\text{trk}}^{\text{ref}}$ intervals. A different approach is undertaken using Method 2, where the cumulants are calculated for reference particles ($N_{\text{trk}}^{\text{ref}}$) but events are selected with a fixed multiplicity of $N_{\text{trk}}(p_T > 0.4 \text{ GeV})$. With this event selection, the cumulants are obtained for fluctuating multiplicities of reference particles.

Figure 8 shows a comparison of $c_2\{4\}$ obtained with Method 1 and Method 2 for pp collisions at 13 TeV. Reference particles with $0.3 < p_T < 3$ GeV are used. The CMS results from Ref. [17] are also shown. The comparison of results obtained with the two methods allows the contribution of event-by-event multiplicity fluctuations to the measured cumulants to be studied. It is found in the data, and also in events generated by PYTHIA8, that multiplicity fluctuations give a negative contribution to $c_2\{4\}$ and, as such, can mimic the collective-like effects. The measurements of cumulants with a method that, by construction, is not susceptible to multiplicity fluctuations do not provide evidence for collectivity. However, even though free of multiplicity fluctuations, the standard procedure used to calculate $c_2\{4\}$ can be still biased by non-flow correlations, and so the question of collectivity from a cumulant-based

approach remains open.

Figure 8: Comparison of $c_2\{4\}$ cumulants obtained with Method 1 and Method 2 for pp collisions at 13 TeV [16]. The plot shows results for reference particles with $0.3 < p_T < 3.0$ GeV. The error bars and shaded bands denote statistical and systematic uncertainties, respectively. The CMS results from Ref. [17] are also shown as open squares.

Azimuthal anisotropies in pp and $p+\text{Pb}$ systems

Two-charged-particle correlations have been measured by ATLAS in pp collisions at 5.02 and 13 TeV and in 5.02 TeV $p+\text{Pb}$ collisions [18]. This measurement uses integrated luminosities of 64 nb^{-1} for the 13 TeV pp data, 170 nb^{-1} for 5.02 TeV pp data and 28 nb^{-1} for 5.02 TeV $p+\text{Pb}$ data. A template fitting procedure developed for pp collisions [19] is utilised systematically in all data sets. The correlation functions are measured for different intervals of measured charged particle multiplicity ($N_{\text{ch}}^{\text{rec}}$) and FCal transverse energy and for different intervals of charged-particle transverse momentum; many of the results are presented for an inclusive p_T interval of $0.5 < p_T < 5$ GeV.

In addition to the elliptic, $\cos(2\Delta\phi)$, modulation observed in a previous measurement, the pp correlation functions are found to exhibit significant $\cos(3\Delta\phi)$ and $\cos(4\Delta\phi)$ modulation. The Fourier coefficients $v_{n,n}$ associated with the $\cos(n\Delta\phi)$ modulation of the correlation functions for $n = 2-4$ are measured as a function of charged-particle multiplicity and charged-particle transverse momentum. Amplitudes of flow harmonics are found to have a similar p_T dependence in both systems, however, they exhibit a systematically different magnitude.

A direct test of the similarity of the p_T dependence of the Fourier coefficients in pp and $p+\text{Pb}$ collisions is provided in Figure 9 for $n = 2$. The pp v_2 values have been multiplied by 1.51 to match the $v_2(p_T^a)$ function at maximum. The resulting $v_2(p_T^a)$ values for (scaled) pp and $p+\text{Pb}$ agree well for p_T^a up to 5 GeV. At higher p_T^a

the pp v_2 decreases more rapidly due to the multiplicity-dependent change in the shape of the dijet peak in the two-particle correlation function at high p_T . After the scaling, the pp $v_2(p_T^a)$ are slightly higher than the $p+Pb$ at low p_T^a , but the similarity of the shapes of the p_T dependence is, nonetheless, striking.

Figure 9: Comparison of the shapes of the $v_2(p_T)$ in the 13 TeV pp and 5.02 TeV $p+Pb$ data [18]. The pp v_2 has been scaled by a factor of 1.51 along the y-axis in order to match the maximum of the v_2 in the two data sets. The results are for $0.5 < p_T^b < 5$ GeV and $N_{ch}^{rec} \geq 60$. The error bars indicate statistical uncertainties.

Figure 10 shows v_4/v_2^2 versus N_{ch}^{rec} for the 13 TeV pp and $p+Pb$ data. In the ratio, the correlated systematic uncertainties between the measured v_4 and v_2^2 cancel. The ratio is observed to be constant as a function of N_{ch}^{rec} for both data sets even though the $p+Pb$ v_2 and v_4 increase with N_{ch}^{rec} . The v_4/v_2^2 ratio is observed to be 50% larger in the pp data than in the $p+Pb$ data. Naively, this would indicate a larger non-linear contribution to v_4 in pp collisions compared to $p+Pb$ collisions.

Figure 10: Ratio of v_4 to v_2^2 as a function of N_{ch}^{rec} in the 13 TeV pp and 5.02 TeV $p+Pb$ data [18]. The results are for $0.5 < p_T^{a,b} < 5$ GeV. The error bars and shaded bands indicate statistical and systematic uncertainties, respectively.

7. Summary

The ATLAS Collaboration has performed multiple measurements on heavy-ion data collected at the center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV provided in the heavy-ion run in 2015. They involve soft and hard probes and aim to elucidate the short- and long-wavelength properties of the QGP. Results of azimuthal and multi-particle correlations in both pp and $Pb+Pb$ systems have been shown as examples of soft-sector measurements. An impact of the QGP medium on quarkonia and jets have been discussed in the context of J/ψ and $\psi(2S)$ production as well as photon-jet correlations. Availability of pp data collected at the same energy as the $Pb+Pb$ system allows for direct comparisons of various observables between two collision systems. In addition, old Run 1 $p+Pb$ data collected at $\sqrt{s_{NN}} = 5.02$ TeV could be reinterpreted thanks to the new pp reference sample. That allows for a better precision in measurement sensitive to nuclear modifications to parton distribution functions. Furthermore, larger luminosity and energy available in Run 2 makes it possible to provide an evidence of light-by-light scattering in $Pb+Pb$ collisions for the first time.

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