

RECENT ATLAS RESULTS IN HEAVY-ION AND ULTRA-PERIPHERAL COLLISIONS*

TOMASZ BOLD 

on behalf of the ATLAS Collaboration

AGH University of Krakow
al. Adama Mickiewicza 30, 30-059 Kraków, Poland

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The ATLAS experiment at the Large Hadron Collider performs a broad heavy-ion physics programme aimed at studying strongly interacting matter at extreme energy density, as well as probing QCD and electroweak phenomena in nuclear environments. This contribution presents an overview of recent ATLAS results obtained in heavy-ion, light-ion, and ultra-peripheral collisions. Measurements include jet quenching observables in Pb+Pb and O+O collisions, top-quark observation in Pb+Pb collisions, collective behaviour in heavy-ion and light-ion systems, photon-induced processes in ultra-peripheral collisions, and searches for physics beyond the Standard Model.

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1. Introduction

Heavy-ion collisions at the Large Hadron Collider (LHC) allow the study of strongly interacting matter at extreme temperatures and energy densities where the quark–gluon plasma (QGP) is formed. The ATLAS [1] detector, with its large acceptance and excellent tracking, calorimetry, and muon systems enables measurements of a wide range of probes including jets, heavy flavours, electroweak bosons, and top quarks.

Data collected during Run 2 and Run 3 at nucleon–nucleon centre-of-mass energies of $\sqrt{s_{NN}} = 5.02$ and 5.36 TeV enable precision studies of parton energy loss, medium response, and collective phenomena. In addition to heavy-ion collisions, the LHC has recently delivered light-ion systems such as O+O and Ne+Ne collisions, allowing the exploration of QGP-like effects

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in smaller systems. Ultra-peripheral collisions (UPC), where the impact parameter exceeds twice the nuclear radius, provide access to photon-induced processes as well as a convenient experimental environment for searches for New Physics in the electromagnetic sector.

2. Jet quenching and QGP probes in heavy- and light-ion collisions

Jets produced in the initial hard scatterings of heavy-ion collisions serve as sensitive probes of the hot and dense QGP medium. One of the most direct observables of the interaction of QCD objects with QGP is the so-called jet quenching. Its primary manifestations are the reduction of inclusive jet rates quantified by the nuclear modification factor

$$R_{AA} = \frac{1}{N_{\text{evt}} \langle T_{AA} \rangle d\sigma_{pp}/dp_T} \frac{dN_{\text{jet}}}{dp_T},$$

which is defined as a ratio of jet production yields in nucleon–nucleon collisions to the cross section in pp , scaled by the so-called nuclear thickness $\langle T_{AA} \rangle$, taking care of the fact that the nucleus is composed of multiple nucleons. In the more recent ATLAS measurement, insight into jet quenching is obtained by studying R_{AA} of jets that have different substructures [2]. The variable R_{AA} as a function of the angular separation between the hardest splittings, dR_{12} , in large-radius jets is studied. As shown in figure 1, a decreasing R_{AA} is observed at small angular separations, while a plateau appears at larger angles, which may indicate the onset of coherent radiation in the medium. An inflection point in R_{AA} at radii of about 0.12 is hinted by data as the angular separation beyond which the QGP interacts coherently with jet constituents.

The second important quantity that is sensitive to jet interactions in the QGP is the dijet momentum balance

$$x_J = \frac{p_{T,2}}{p_{T,1}},$$

where $p_{T,1}$ and $p_{T,2}$ denote the transverse momenta of the leading and sub-leading jets, respectively. In pp collisions, the distribution peaks near unity, while in Pb+Pb collisions, especially in central ones, the distribution becomes significantly broadened. This effect has been studied extensively in the past and indicates parton energy loss in the medium [3].

Studies of x_J in light-ion collisions allow the exploration of the transition between proton–nucleus and heavy-ion collisions. ATLAS collected approximately 8 nb^{-1} of O+O data that has sufficient statistics for the relevant x_J measurement. It should be noted that O+O data is considerably easier

to analyze compared to Pb+Pb due to the reduced underlying event. Using this data set, the dijet asymmetry measurement is performed. It shows that peripheral O+O events resemble pp collisions, while central collisions exhibit a broadened x_J distribution, suggesting the onset of jet-quenching effects in small systems [4]. An example of the x_J distribution for the lowest studied jet momenta is shown in figure 1.

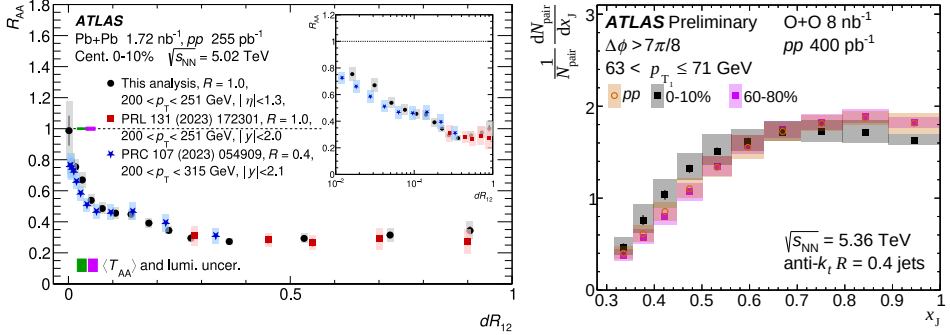


Fig. 1. Left: Nuclear modification factor R_{AA} of jets as a function of angular separation of two sub-jets in Pb+Pb collisions [2]. Right: Comparison of dijet asymmetry, x_J in pp , peripheral (60–80%) and central (0–10%) O+O collisions [4].

A new probe of the QGP was established with the first observation of top-quark pair production in heavy-ion collisions. ATLAS measured the $t\bar{t}$ production cross section in Pb+Pb collisions using the opposite-sign $e^\pm\mu^\mp$ decay channel: $\sigma_{t\bar{t}} = 3.6 \pm 1.0(\text{stat.})^{+0.9}_{-0.8}(\text{syst.}) \mu\text{b}$. The result is consistent with expectations from pp data and nuclear parton distribution functions [5]. This observation opens new possibilities for using top quarks as calibrated probes of the QGP.

2.1. Bulk QGP properties

Another angle at which the QGP can be studied focuses on the bulk properties. A recently introduced observable sensitive to radial expansion is utilized to prove experimentally that the radial flow (increase of particles mean transverse momenta) is a collective phenomenon [6]. It is quantified by the v_0 which is a correlation between the change in multiplicity and change of charged tracks mean p_T , $[p_T]$

$$v_0(p_T)v_0 = \frac{\langle \delta n(p_T) \delta [p_T] \rangle}{\langle n(p_T) \rangle \langle [p_T] \rangle},$$

where n stands for charged tracks multiplicity and averaging $\langle \rangle$ runs over events. The confirmation of the collective nature of radial flow is based on

the observation of three important properties of any collective phenomenon in nucleus–nucleus collisions: long range in η , factorization in transverse momenta, and centrality independent shape. All three of these are investigated and confirmed. Also, the new observable, $v_0(p_T)/v_0$, shown in figure 2, turns out to be uniquely sensitive to QGP bulk viscosity that is otherwise weakly constrained.

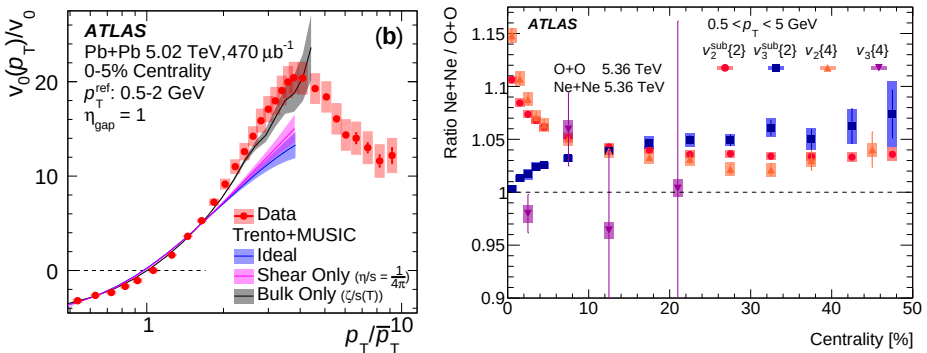


Fig. 2. Left: The radial flow p_T dependence in central Pb+Pb events compared to hydrodynamical model predictions including or not bulk-viscosity [6]. Right: The ratio of flow harmonics v_2 and v_3 measured with two- and four-particle correlations between Ne+Ne and O+O collisions as a function of collision centrality [7].

The light-ion collisions are also investigated for the presence of collectivity. As both nuclei are of comparable size, the observed differences are understood as originating from the initial state generated by different initial geometries. For that purpose, azimuthal anisotropy coefficients v_n for $n = 2-4$ in O+O and Ne+Ne collisions are obtained. Subtle differences, most importantly larger v_2 in Ne+Ne events, consistent with the more elongated shape of Ne nucleus are observed [7].

3. Ultra-peripheral collisions

Ultra-peripheral collisions occur when the impact parameter between nuclei exceeds twice the nuclear radius, suppressing hadronic interactions while enabling photon-induced processes. It is a perfect environment to study EM processes at the highest energies, benefiting from a nearly background free environment, as well as to use photons as a probe of cold QCD effects.

3.1. Exclusive di-tau production and search for magnetic monopoles

ATLAS measured the exclusive process $\gamma\gamma \rightarrow \tau^+\tau^-$ in Pb+Pb UPC events using Run 2 data [8, 9]. The goal of the analysis was to search for

deviations of the τ anomalous magnetic dipole moment from the Standard Model (SM). This measurement is of high interest, as deviations from SM predictions are seen for muons [10]. For the τ lepton, due to its mass, the differences should be more pronounced. The analysis requires at least one leptonic τ decay and low detector activity consistent with exclusive production. The channels with one of the taus decaying into a muon of $p_T > 4$ GeV and the second decaying into an electron or hadronically with 1 or 3 charged tracks are analysed.

The measured cross sections as a function of muon p_T , track p_T , and other kinematical variables are obtained. They are largely consistent with theoretical predictions while still providing discriminating power between models, as shown in figure 3.

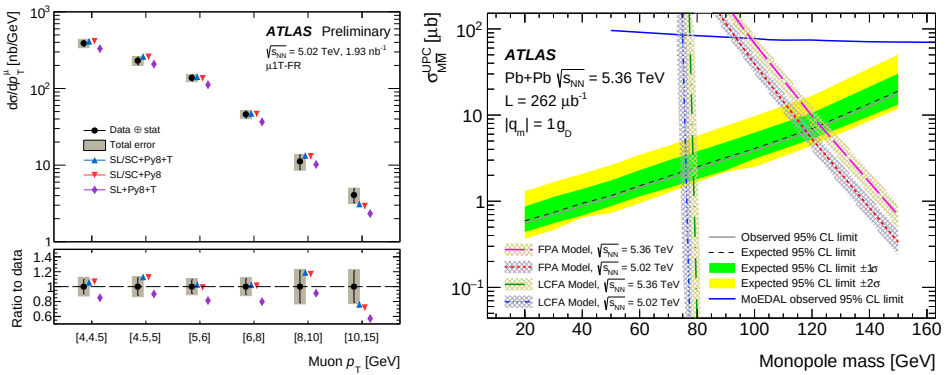


Fig. 3. Left: The fiducial cross section of $\gamma\gamma \rightarrow \tau\tau \rightarrow \mu + 1 - \text{track}$ as a function of muon p_T in UPC Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [9]. Right: The upper limits on magnetic monopoles production in Pb+Pb UPC at $\sqrt{s_{NN}} = 5.36$ TeV collisions [11].

Another beyond-SM measurement performed by ATLAS is a search for magnetic monopoles produced via a mechanism analogous to the Schwinger process in strong electromagnetic fields. The analysis looks for events with large pixel-detector activity caused by the highly ionizing nature of monopoles without associated tracks. The number of such events is found to be consistent with beam-induced background. The results, shown in figure 3, set the most stringent limits to date on monopole production in the mass range 20–140 GeV [11].

3.2. Coherent J/ψ photoproduction and coincident UPC processes

Coherent photoproduction of vector mesons probes gluon distributions in nuclei at small Bjorken- x . In leading order of QCD, the cross section

is proportional to gluon PDFs squared in phase-space defined by low- x . While nuclear shadowing occurs in these conditions, it is expected that the phenomena of parton saturation also take place in this case. The effect should be enhanced when protons or neutrons are confined in a large nucleus. Thus, the cross section of vector-meson production like J/ψ would saturate, and this saturation would vary with rapidity as $x = m_{J/\psi}/\sqrt{s_{NN}} e^{\pm y_{J/\psi}}$. Therefore, ATLAS measured the differential cross section for exclusive coherent J/ψ production as a function of rapidity in Pb+Pb UPC collisions at $\sqrt{s_{NN}} = 5.36$ TeV [12]. The measurement used Run 3 data and benefited from single-track trigger implemented in the ATLAS Transition Radiation Tracker. Calculations based on the colour-glass condensate framework with nucleon shape fluctuations [13] provide the best description of the data. The results are also compared to those of CMS and ALICE, and good agreement is observed at forward rapidities, while a tension is observed when J/ψ is produced at central rapidities, as shown in figure 4.

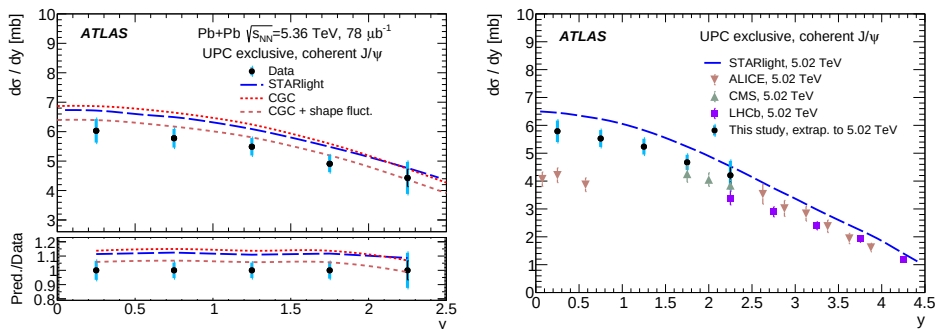


Fig. 4. Left: The cross section of $\gamma A \rightarrow J/\psi \rightarrow \mu\mu$ as a function of di-muon rapidity in Pb+Pb UPC at $\sqrt{s_{NN}} = 5.36$ TeV. The comparison of measured cross section to various theoretical models (left) and experiments (right) [12].

To further investigate the source of the tension between the experimental results, ATLAS also measured coincident photon-induced processes. In this measurement, simultaneous di-muon production and ρ^0 photoproduction were studied. A non-negligible rate of such processes was observed. The probability of these processes depends strongly on the impact parameter inferred from forward neutron emission [14] and to a lesser extent on other di-muon system properties considered to be correlated with the impact parameter. This rate is shown in figure 5.

UPC collisions were also investigated for signs of collectivity. For this purpose, the strange-hadron production in photonuclear interactions was studied through measurements of K_S^0 , Λ , and Ξ^- yields as a function of

charged-particle multiplicity. Hints of strangeness enhancement are observed at high multiplicities, consistent with collective phenomena observed in other collision systems [15].

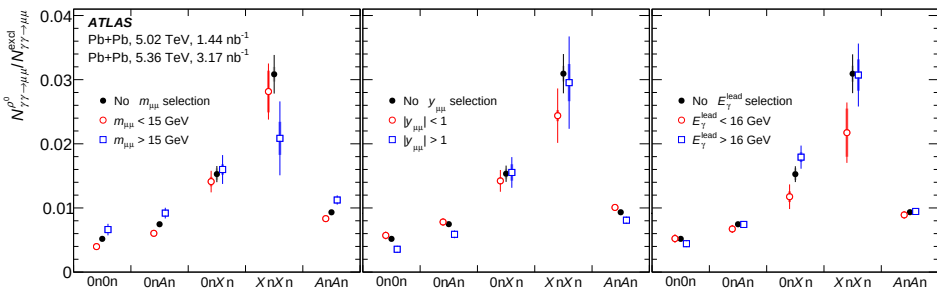


Fig. 5. The rate in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 5.36 TeV combined [14].

4. Summary

The ATLAS heavy-ion programme continues to provide new insights into QCD matter under extreme conditions. Measurements of jet quenching, jet substructure, and top-quark production in Pb+Pb collisions provide new insights to the QGP properties. Light-ion collisions enable studies of the onset of collective phenomena in smaller systems, while ultra-peripheral collisions probe photon-induced interactions and offer opportunities to search for New Physics. The data from the entire Run 3 is the subject of ongoing analyses and will be a source of further exciting results.

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