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Heavy ion physics in ATLAS and CMS

M. Dyndal on behalf of the ATLAS and CMS Collaborations
AGH University of Science and Technology - Krakow, Poland

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Summary. — An overview of the latest heavy-ion measurements with the ATLAS and CMS detectors at the LHC, utilizing the high statistics 5.02 TeV Pb+Pb data collected in 2015 and 2018, is given. These include multiple measurements of jet production and structure, which probe the dynamics of the hot and dense medium (quark-gluon plasma) formed in relativistic nucleus-nucleus collisions; measurements of quarkonia and heavy flavor production to probe the medium properties; and various measurements of ultra-peripheral collision processes.

1. – Introduction

The ATLAS and CMS experiments [1, 2] at the LHC carry out an extensive program to probe and characterize the hot and dense quark-gluon plasma (QGP) created in relativistic heavy-ion (HI) collisions. In addition, the electromagnetic (EM) fields of the ions, can initiate photon-induced interactions, especially at large impact parameters where the strong interaction is not active (ultraperipheral collisions, UPC).

Section **2** of this report summarizes the latest results on the jet production in HI collisions. Section **3** covers results on physics of heavy-flavor hadrons. Section **4** discusses measurements involving photon–photon collisions and sect. **5** summarizes new results on collectivity in photonuclear systems.

2. – Jet measurements

Jets – narrow cones of hadrons and other particles produced by the hadronization of quarks or gluons – are considered as one of the key probes of QGP.

The energy loss from partons is expected to depend on the length of the QGP region that the parton traverses. The geometry of the overlapping nuclei in mid-central collisions leads to shorter average path lengths if the jet is oriented along the direction of the collision impact parameter vector than if the jet is oriented in the perpendicular direction. The new ATLAS analysis extends the original measurements of jet v_2 to higher jet transverse momenta [3]. Figure 1 shows the measured values of v_2, v_3 and v_4 as a function of collision centrality. A nonzero value of jet v_2 is observed in all but the most central

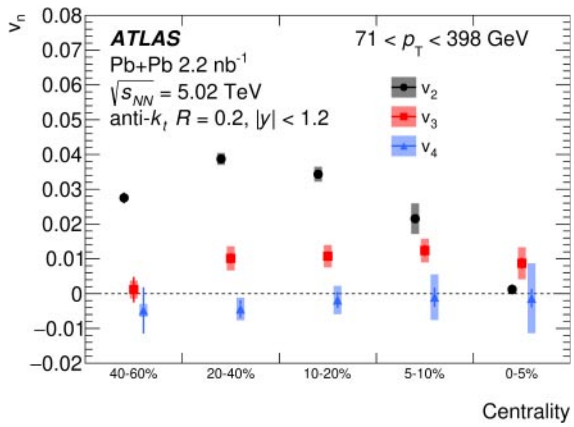

Fig. 1. – Jet v_2, v_3 and v_4 as a function of centrality for jets with p_T = 71–398 GeV [3].

collisions. The value of v_2 is largest for jets with lower transverse momentum, with values up to 0.05 in mid-central collisions. A smaller, nonzero value of v_3 of approximately 0.01 is measured with no significant dependence on jet transverse momentum or centrality, suggesting that fluctuations in the initial state play a small but distinct role in jet energy loss. No significant deviation of v_4 from zero is observed in the measured kinematic region.

Inclusive jet spectra reconstructed using different radius parameter (R) are of great interest because they are less sensitive to hadronization effects than observables involving individual final-state hadrons. By varying R, different fractions of energy from the quenched jet and the medium response are included in the reconstructed jet. Measurements of jet nuclear modification factors (R_{AA}) with a distance parameter R up to 1.0 are performed by CMS [4]. Figure 2 shows $R^R_{AA}/R^{R=0.2}_{AA}$ as a function of R for several values of jet transverse momentum. The $R^R_{AA}/R^{R=0.2}_{AA}$ has little dependence upon R and is consistent with unity for all values of jet transverse momentum, which is captured by some of the theoretical predictions.

3. – Production of heavy-flavor hadrons

Heavy quarks, charm and bottom, have masses much larger than the QGP temperature. Thus, they are produced in the initial collision via high-momentum-transfer interactions between incident quarks and gluons, where thermal production is highly suppressed. The strong-force interactions conserve the quantum numbers associated with the charm and bottom quarks. Thus, once created, these quarks can have substantial modifications to their momentum distributions when traversing the QGP, but they cannot be destroyed.

A measurement of the muons from semileptonic decays of charm and bottom hadrons in Pb+Pb collisions is performed by ATLAS [5]. Muons from heavy-flavor semileptonic decays are separated from the light-flavor hadronic background using the momentum imbalance between the inner detector and muon spectrometer measurements, and muons originating from charm and bottom decays are further separated via the muon track's transverse impact parameter. Nuclear modification factors (R_{AA}) for charm and bottom

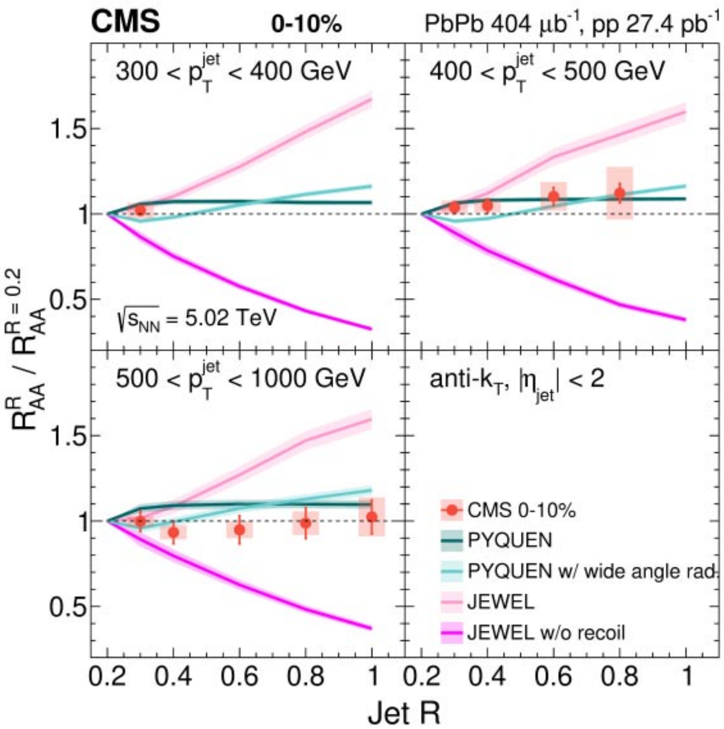

Fig. 2. – The R_{AA} ratio for jets as a function of R for $R = 0.3 - 1.0$ with respect to $R = 0.2$, in various jet transverse momentum ranges for the 0-10% centrality class [4]. The theory predictions, shown with the colored bands, are compared to the data.

muons are measured as a function of muon transverse momentum in intervals of Pb+Pb collision centrality. The measured R_{AA} quantify a significant suppression of the yields of muons from decays of charm and bottom hadrons, with stronger effects for muons from charm hadron decays.

B_c^+ mesons contain both b and c quarks, and measurements of its properties can bridge the gap between charmonia and bottomonia, and provide an additional probe of the heavy-quark potential. The B_c^+ meson can also provide unique insight into the interplay of suppression and enhancement mechanisms in the production of heavy mesons in the QGP. They can be detected through their $B_c^+ \to J/\psi\mu\nu$ decays by searching for three muons among which there is an opposite-sign pair with mass consistent with a J/ψ meson. CMS carried out the first observation of the production of B_c^+ mesons in Pb+Pb collisions [6]. Figure 3 shows the measurement of the nuclear modification factor for B_c^+ meson. No significant variation from unity is observed as a function of centrality.

The $X(3872)$ is an exotic particle whose nature is still not fully understood and interpretations in terms of the conventional charmonium bound state, D-meson molecules or tetraquark states have been proposed. It is expected that in HI collisions, the formation of the QGP could modify the production rate of the $X(3872)$ particle. For example, coalescence mechanisms could enhance the X(3872) production yield. The first evidence for $X(3872)$ production in HI collisions, with a significance of 4.2 standard deviations,

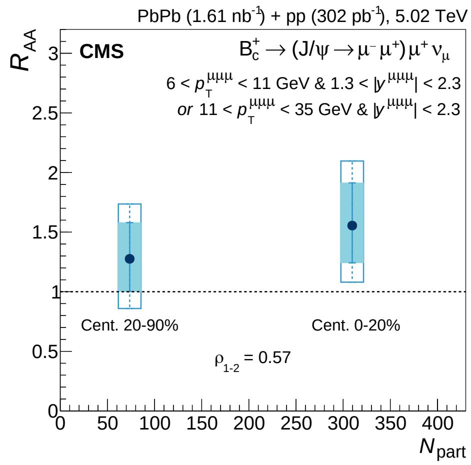

Fig. 3. – The nuclear modification factor for B_c^+ meson in centrality bins integrated over the studied kinematic range [6].

is reported by CMS [7]. The $X(3872)$ candidates are reconstructed through the decay chain $X(3872) \to J/\psi\pi\pi \to \mu\mu\pi\pi$. The prompt $X(3872)$ to $\Psi(2S)$ yield ratio is found to be 1.08 ± 0.49 (stat.) ± 0.52 (syst.), to be compared with typical values of 0.1 for pp collisions. The measurement provides new input to theoretical models of the $X(3872)$ production mechanism, and of the nature of this exotic state.

4. – Measurements of photon–photon interaction

Photon–photon fusion is a rare process at ion colliders. It is particularly interesting as a remarkably clean interaction with little (if any) remnant activity from the interacting particles.

ATLAS has measured the cross sections for exclusive dimuon production ($\gamma\gamma \to \mu\mu$) in UPC Pb+Pb collisions for dimuon invariant masses ($m_{\mu\mu}$) above 10 GeV [9]. The cross sections are extracted by selecting events using a single-muon trigger, in association with an otherwise low charged particle multiplicity event. The events are required to have two oppositely-charged muons, each having transverse momentum $p_{\mathrm{T}} > 4$ GeV and pseudorapidity $|\eta| < 2.4$, with dimuon transverse momentum below 2 GeV. The events are then categorized with respect to energy deposits in Zero Degree Calorimeters (ZDC), which are sensitive to neutrons emitted as a result of Pb ion excitation due to multiple Coulomb interactions accompanying the $\gamma\gamma \to \mu\mu$ process. Three categories are defined (0n0n, Xn0n and XnXn) which reflect the ZDC energy activity on either side of the ATLAS detector. Here 0n denotes no neutron emission and Xn denotes any neutron emission. The background, dominated by dissociative dimuon production where one photon is emitted by charged constituents of a nucleon, is estimated using template fits to dimuon acoplanarity (defined as $\alpha = 1 - |\Delta\phi|/\pi$). This background is negligible for the 0n0n category, but it rises to 7% for Xn0n and to 12% for XnXn categories. The results are compared with calculations from the STARlight 2.0 MC generator [10], corrected for FSR effects using Pythia 8 [11], as presented in fig. 4. Generally, good agreement is found but some systematic differences are seen, which may be explained by deficiencies in the modeling of the incoming photon flux.

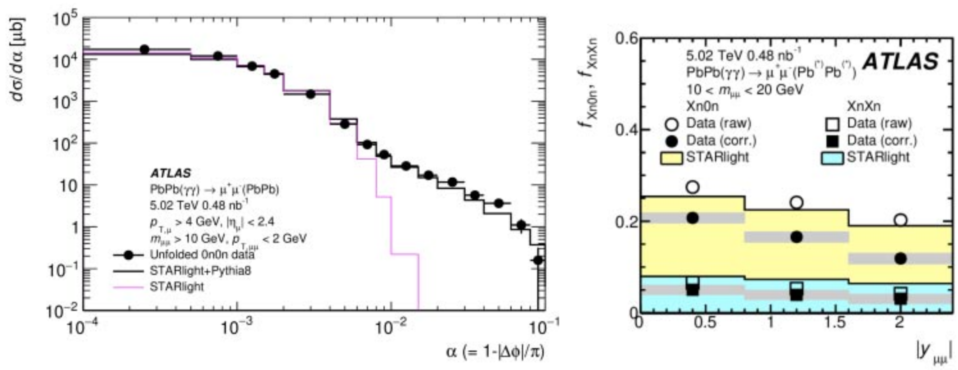

Fig. 4. – (left) Differential cross sections dσ/dα for $\gamma\gamma \to \mu\mu$ process in data from the 0n0n category [9]. Data are compared to the cross sections from STARlight with, and without, Pythia 8 QED showering. (right) Fractions of events with Xn0n and XnXn, as a function of absolute dimuon rapidity for $10 < m_{\mu\mu} < 20$ GeV [9]. Data are shown as raw (open circles) and fully corrected for detector effects (closed circles).

Using the same final state, CMS has observed the broadening of the core of the dimuon acoplanarity distribution, when comparing the events between 0n0n, Xn0n and XnXn categories [12]. This subtle effect is due to the fact that the average transverse momentum of photons emitted from relativistic HI has an impact parameter dependence.

Light-by-light (LbyL) scattering, $\gamma\gamma \to \gamma\gamma$, is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics [8]. The LbyL process has been proposed as a sensitive channel to study physics beyond the standard model. For example, new neutral particles, such as axion-like particles (ALP), can contribute to the LbyL cross section in the form of narrow diphoton resonances [13]. ALPs are relatively light, gauge-singlet (pseudo-)scalar particles that appear in many theories with a spontaneously broken global symmetry. Their masses and couplings to standard model particles may range over many orders of magnitude.

Both ATLAS and CMS performed a search for $\gamma\gamma \to a \to \gamma\gamma$ process in UPC data, where a denotes the ALP [14, 15]. Since no significant deviations from the background-only hypothesis are observed, the results are then used to estimate the upper limits on the ALP production at 95% confidence level (CL). Assuming a 100% ALP decay branching fraction into photons, the derived constraints on the ALP mass and its coupling to photons are compared in fig. 5 with those obtained from other experiments. The ALP exclusion limits from ATLAS and CMS analyses are the strongest so far for the mass range of $5 < m_a < 100$ GeV.

5. – Search for collectivity in photonuclear interactions

The azimuthal anisotropies in particle production have been observed in nearly all hadronic collision systems studied so far, from Pb+Pb collisions to *pp* collisions. These are interpreted as resulting from the collective expansion of system reflecting the anistropic pressure gradients from the initial conditions. In order to test if similar effects can be observed in the inclusive photonuclear interactions, ATLAS has studied events

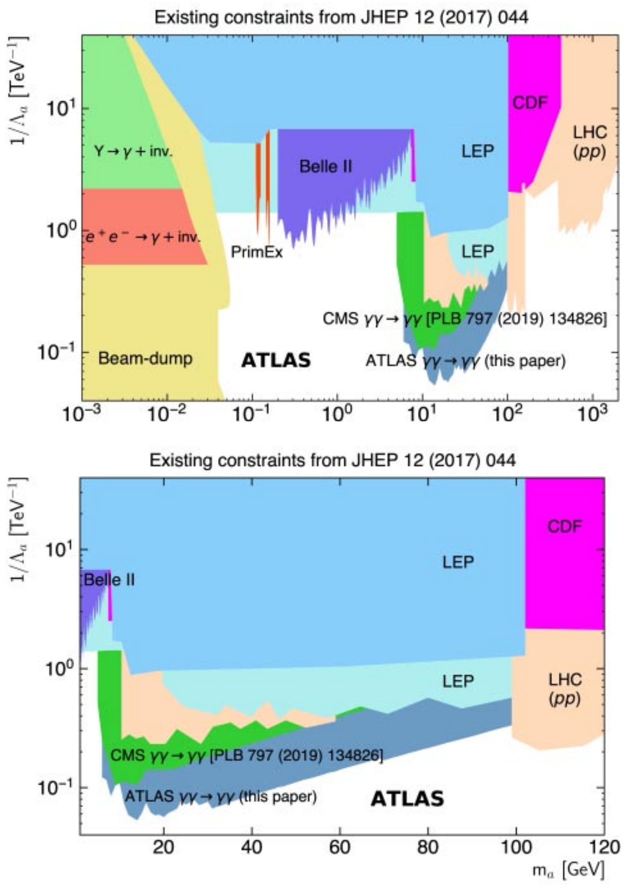

Fig. 5. – Compilation of exclusion limits at 95% CL in the ALP–photon coupling $(1/\Lambda_a)$ *versus* ALP mass (m_a) plane obtained by different experiments [15]. The existing limits are compared with the limits extracted from this measurement. The exclusion limits labelled "LHC (pp)" are based on pp collision data from ATLAS and CMS. All measurements assume a 100% ALP decay branching fraction into photons. The plot on the bottom is a zoomed-in version covering the range $1 < m_a < 120$ GeV.

triggered on the 0nXn ZDC topology, in coincidence with a large gap in the photon-going direction [16]. These events have been classified by their observed charged particle multiplicity, and analyzed through the template fitting technique, using a peripheral multiplicity bin to subtract non-flow contributions. The measurement extracts v_2 coefficient for charged particles which rises as a function of particle transverse momentum (fig. 6). The photonuclear events (in red) show a significant long-range correlation, which is lower than that in pp or p+Pb events. These results could be explained by the vector meson part of the photon wave function, which gives rise to collision conditions similar as those in pp or p+Pb.

Significant v_2 values are also observed in γp-enriched events from p+Pb collisions by CMS [17]. However, this may be due to the effect of jet correlations within the γp enhanced sample. Due to the limited charged-particle multiplicity range for the γp

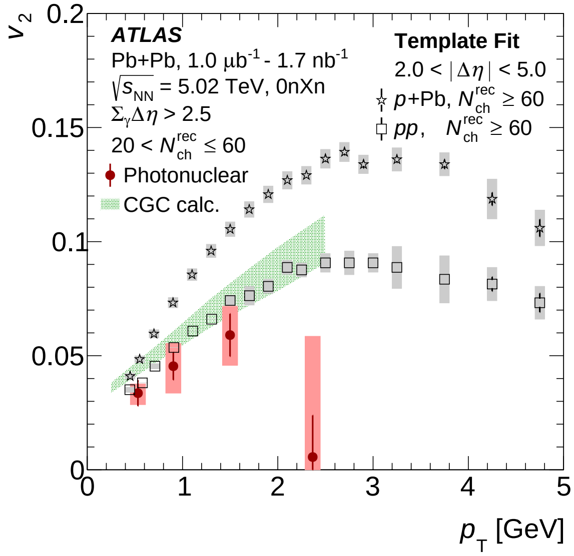

Fig. 6. – Elliptic flow coefficient v_2 measured in photonuclear Pb+Pb events as a function of charged-particle transverse momentum [16].

events, no low-multiplicity subtraction technique is implemented to remove such non-flow contributions.

6. – Conclusions

The ATLAS and CMS experiments at the LHC performed a series of new measurements of jets, quarkonia and heavy flavor in Pb+Pb collisions. These new results provide a precise quantification of suppression effects and collective phenomena.

The new results from the UPC physics programme are also presented. UPC photon–photon interactions allow access to several QED processes, in particular those involving dileptons and photons. They provide a clean environment for studying physics beyond the standard model. In addition, photonuclear (γPb) processes show collective expansion, similarly to that observed in other (small) collision systems.

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