PHYSICS OF RIDGE AND HARD PROCESSES IN PROTON–LEAD AND LEAD–LEAD COLLISIONS WITH ATLAS*

Martin Spousta

on behalf of the ATLAS Collaboration

Institute of Particle and Nuclear Physics
Faculty of Mathematics and Physics, Charles University
V Holešovičkách 2, 180 00 Prague 8, Czech Republic

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In this short report, we provide an overview of selected new results from the heavy-ion physics program of the ATLAS experiment at the LHC with the emphasis on jet quenching, quarkonia suppression and long-range azimuthal correlations.

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1. Introduction

Heavy-ion collisions at ultra-relativistic energies produce a hot, dense medium of strongly interacting nuclear matter understood to be composed of deconfined color charges that is commonly called a quark–gluon plasma (QGP) [1–4]. Studying the QGP and its properties should lead to better understanding of non-perturbative aspects of quantum chromodynamics (QCD) and collective phenomena connected with the strong interaction. Further, it should also lead to an improvement in the understanding of the transition between quarks and gluons and hadrons. Finally, understanding QGP means understanding a matter under extreme conditions, not far from that which was present in early stages of the evolution of the universe. The ATLAS experiment [5] at the LHC has undertaken an extensive program to probe and characterize this hot and dense nuclear matter. In this short report, we provide an overview of selected new results from the heavy-ion program of the ATLAS experiment with the emphasis on jet quenching, quarkonia suppression and long-range azimuthal correlations.

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2. Jets and quarkonia in heavy-ion collisions

In pp, e^+e^-, or ep collisions, hard scattering processes represent the main tools to study perturbative QCD. In lead–lead (Pb+Pb) collisions, products of hard scattering of quarks and gluons evolve as parton showers that propagate through QGP. Parton shower constituents emit medium-induced gluon radiation and, as a consequence, lose energy leading to the production of lower-energy jets. This phenomenon is termed "jet quenching" [6–8]. ATLAS studied this phenomenon in the suppression of inclusive jet yields [9–12], in a modification of jet internal structure [13,14], and a study of dijets [15,16] and multi-jet systems [17]. Modifications of the jet yields in Pb+Pb collisions compared to yields measured in pp collisions can be quantified by the measurement of the nuclear modification factor

$$R_{AA} = \frac{\dfrac{1}{N_{\mathrm{evt}}^{\mathrm{tot}}} \dfrac{\Delta^2 N_{\mathrm{jet}}}{\Delta p_{\mathrm{T}} \Delta y}\Big|_{\mathrm{cent}}}{T_{AA} \dfrac{\Delta^2 \sigma_{\mathrm{jet}}}{\Delta p_{\mathrm{T}} \Delta y}\Big|_{pp}}, \tag{1}$$

where N_{jet} and σ_{jet} are the jet yield in Pb+Pb collisions and the jet cross section in pp collisions, respectively, both measured as a function of transverse momentum (p_{T}) and rapidity (y); $N_{\mathrm{evt}}^{\mathrm{tot}}$ is the total number of Pb+Pb collisions within a chosen centrality interval; and T_{AA} is the nuclear thickness function which accounts for the geometric enhancement of per-collision nucleon–nucleon luminosity. In the 0–10% centrality interval, R_{AA} is approximately 0.45 at $p_{\mathrm{T}} = 100$ GeV, and is observed to grow only slowly with increasing jet p_{T}. A significant suppression (by a factor of 2) persists up to a TeV scale [9].

Modifications of the jet internal structure were recently studied by ATLAS in 2.76 TeV [14] and 5.02 TeV [18] Pb+Pb collisions. The ratios of charged-particle transverse momentum distributions measured in Pb+Pb collisions to those measured in pp were observed to exhibit an enhancement in central collisions for charged particles with $p_{\mathrm{T}} = 1$–4 GeV, a reduction for particles with $p_{\mathrm{T}} = 4$–25 GeV, and an enhancement in the fragment yield for $p_{\mathrm{T}} > 25$ GeV. The magnitude of these modifications decreases in more peripheral collisions. Modifications were observed to exhibit no jet-p_{T} or rapidity dependence. Further, no difference between modifications measured in 2.76 TeV collisions to those measured in 5.02 TeV collisions was observed. Significant modifications of the jet internal structure seen in Pb+Pb collisions can be contrasted with no modification seen in p+Pb [19] which implies that initial-state effects such as modifications of parton distribution functions in the nuclear environment do not play a major role in the Pb+Pb jet structure measurements. Further quantification of the jet quenching

was recently provided by the measurement of the jet fragmentation in γ-jet events [20] and by the measurement of dijet [16] and γ-jet [21] momentum imbalance.

Similarly to a strong suppression of jets, a strong suppression of both prompt and non-prompt J/Ψ and $\Psi(2S)$ mesons in 5.02 TeV Pb+Pb with respect to 5.02 TeV pp collisions was observed [22]. The observed suppression of J/Ψ in the most central Pb+Pb collisions by as much as a factor of five can be contrasted with no or only weak modifications of J/Ψ and $\Psi(2S)$ in p+Pb collisions [23] suggesting again no major role of initial-state effects in Pb+Pb measurement. Contrary to charmonia, bottomonia were observed to be suppressed in p+Pb collisions [23]. The role of initial-state effects and our understanding of the geometry of nuclear collisions was further studied in inclusive prompt photon in p+Pb collisions [24], Z-boson [25] and W-boson [26] measurements in lepton decay channels in Pb+Pb collisions. A summary of suppression measurements in Pb+Pb collisions in terms of R_{AA} is plotted in Fig. 1.

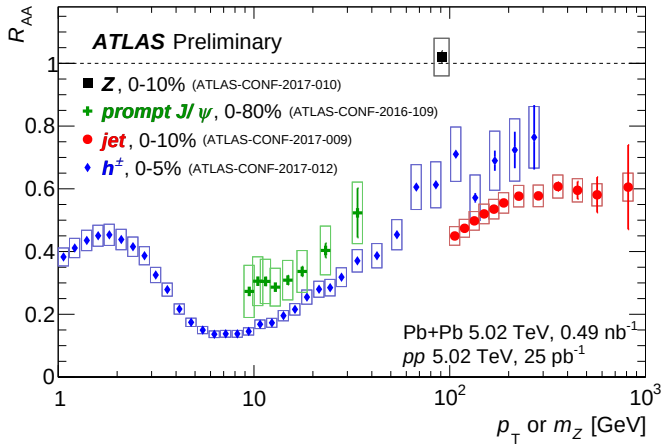


Fig. 1. Compilation of results for the nuclear modification factor R_{AA} *versus* p_{T} or Z-boson mass (m_Z) in different channels from the Run 2 Pb+Pb and pp data. Results are shown for Z bosons (black squares, plotted at m_z), jets (red circles), charged hadrons (blue diamonds) and prompt J/Ψs (green crosses). The error bars and shaded bands indicate statistical and systematic uncertainties, respectively. Figure taken from Ref. [27].

3. Physics of ridge and collective flow

One of the main goals of heavy-ion physics is to characterize properties of QGP. Properties related to the collective expansion of QGP (such as the equation of state and shear viscosity) can be inferred from modulations of the single-particle azimuthal angle distributions measured in

collisions of two nuclei. These modulations are typically characterized using a set of Fourier coefficients v_n that describe the relative amplitudes of the harmonic components of the single-particle distributions, $\Delta N/\Delta\phi \approx 1+2\sum_{n=1}^{\infty} v_n \cos[n(\phi-\Phi_n)]$. The v_n and Φ_n denote the magnitude and orientation of the single-particle anisotropies. The non-zero v_n in heavy-ion collisions are understood to result from large initial pressure gradients in overlap zone of colliding nuclei, which transform the initial spatial anisotropies of the nuclear overlapping zone into momentum anisotropies of the final-state particle production. These modulations are expected in collisions of two nuclei and well-described by calculations based on relativistic hydrodynamics [28].

Recent measurements by ATLAS of two-particle correlations in relative azimuthal angle $\Delta\phi$ and pseudo-rapidity separation $\Delta\eta$ in pp collisions show the presence of correlations in $\Delta\phi$ at large η separation [29, 30]. These long-range correlations, often called "ridge", were shown to be consistent with the presence of a $\cos(n\phi)$ modulation of the single particle azimuthal angle distributions. This modulation is similar to the one seen in Pb+Pb and p+Pb collisions [31], and it represents an unexpected manifestation of collectivity in high-multiplicity (HM) pp collisions. The v_2 measurements in small systems (pp and p+Pb) are summarized in Fig. 2.

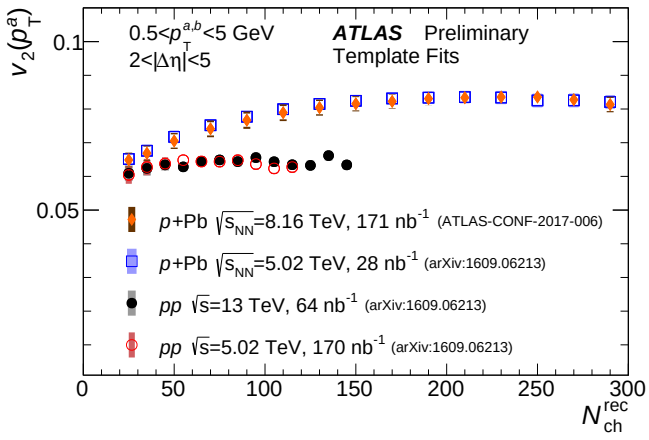


Fig. 2. Comparison of the second-order azimuthal harmonic v_2 obtained from the template fitting procedure in the 13 TeV pp, 5.02 TeV pp, 5.02 TeV p+Pb and 8.16 TeV p+Pb data, as a function of number of charged particles in the event. The error bars and shaded bands indicate statistical and systematic uncertainties, respectively. Figure taken from Ref. [27].

More information on the collectivity in pp collisions may be gained from recent analysis of the ridge in high-multiplicity pp collisions tagged by a presence of Z boson [32], where selecting of high-Q^2 processes may select pp collisions with smaller impact parameters. In Z-tagged events, the v_2 is observed to be $8\% \pm 6\%$ larger compared to the inclusive HM events. More information on the collectivity in p+Pb collisions may be gained from a recent analysis of flow in $D^{*\pm}$-hadron correlations which shows a finite v_2 signal smaller than that of charged particles [33].

4. Summary

In this short report, we provide an overview of selected new results from the heavy-ion program of the ATLAS experiment on jets, quarkonia production and long-range azimuthal correlations. Full list of results can be found on ATLAS results web pages [27].

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