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Recent Heavy Ion Results from the ATLAS Experiment

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The ATLAS experiment at the Large Hadron Collider (LHC) has undertaken a broad physics program to probe and characterize the hot nuclear matter created in relativistic lead-lead collisions. This overview presents recent results on bulk particle collectivity and hard probes, the jets and heavy flavor production, measured in Pb+Pb, p+Pb and *pp* collisions at the LHC energies.

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1. Introduction

In heavy ion collisions a study of the strongly-coupled Quark Gluon Plasma (QGP), a state of matter predicted in quantum chromodynamics theory (QCD), is performed. To determine plasma properties we measure in ATLAS characteristics of soft and hard probes, the low- and high-transverse momentum particles created in the collision. The soft probes bring information about collective effects coming from initial conditions and affecting the evolution of the collision while hard probes test matter properties via modification of energetic parton showers. Since QGP is expected to be produced in larger volumes only in collisions of heavy ions one can isolate these effects by comparing results obtained in heavy ion collisions to those measured in lighter systems, in proton-nucleus and *pp* collisions.

2. Collective phenomena

A collective phenomenon of harmonic flow of particles was first observed in heavy ion collisions at RHIC and later at the LHC collider as an azimuthal angle (ϕ) asymmetry in particle momenta described by $\sum v_n \cos n(\phi - \Phi_n)$ modulation with v_n amplitudes measuring flow strength [1]. ATLAS first measured it using the event plane method in collisions of Pb+Pb ions at the energy of 2.76 TeV/N [2]. The flow amplitudes in these collisions have been found largest in mid-central collisions and for particles with intermediate transverse momenta, $p_T = 3-4$ GeV and with decreasing magnitude for higher order amplitudes [2]. In the same analysis ATLAS used another method, the two-particle azimuthal correlations, to study collective effects. The two-particle correlation function, $C(\Delta\eta, \Delta\phi)$ has been calculated as a ratio of the number of particle pairs in bins of pseudorapidity and azimuthal angle measured in the same event and in mixed events. In Pb+Pb collisions and in high-multiplicity events, the correlation function exhibits some interesting features, namely an enhancement around $\Delta\phi = 0$ called ridge and a wide double hump structure around $\Delta\phi = \pi$, shown here in the left plot in Fig. 1. It was found that these structures come from harmonic flow since their $v_{n,n}$ Fourier expansion parameters factorize to single particle ones, as it was shown in [2].

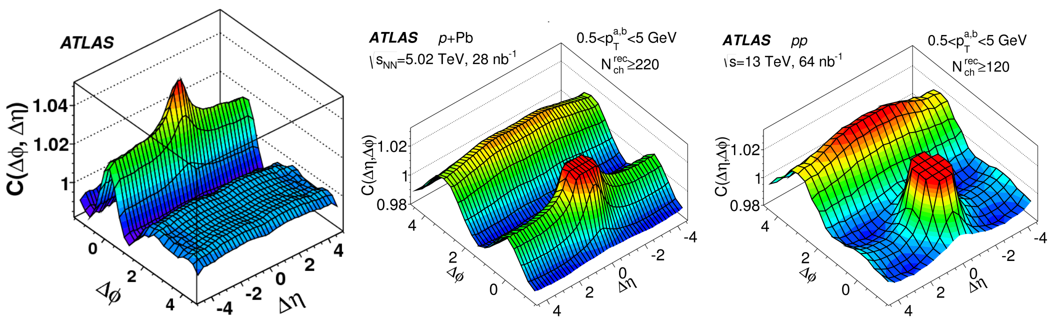

Figure 1: Two-particle correlation functions, $C(\Delta\eta, \Delta\phi)$, in 2.76 TeV Pb+Pb [2], 5.02 TeV p+Pb and 13 TeV *pp* [5], high-multiplicity collision events.

In lighter systems it was assumed that the transverse size of the produced system is too small to develop hydrodynamic flow. However, when ATLAS measured two-particle correlations in p+Pb and later in pp it discovered in high-multiplicity events a ridge structure similar to what was seen in Pb+Pb collisions, see Fig. 1. In order to study the origin of the ridge correlations in p+Pb collisions, a ZYAM (zero yield at minimum) method was used to remove contributions from a jet recoil seen in peripheral collisions [3]. Comparing single and two-particle Fourier expansion parameters it was found that correlation structures in p+Pb collisions come mainly from harmonic flow effects and their strength dependence on transverse momentum of particles is similar to that observed in Pb+Pb collisions, as shown in Fig. 2.

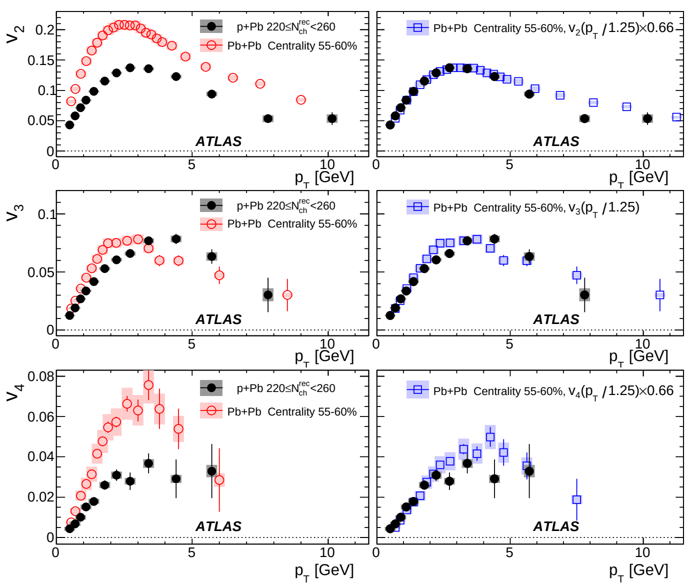

Figure 2: Comparison of flow amplitudes $v_2 - v_4$, shown as functions of p_T, in p+Pb and Pb+Pb collisions (left) and with the same Pb+Pb data rescaled to match the p + Pb data (right) [3].

Later, in another analysis [4], the ridge structure was found also in high-multiplicity events of pp collisions at the energies of 2.76 TeV and 13 TeV. Seeing it was a big surprise since collective effects developing in extended volumes of created matter are not expected to happen in collisions of protons. In these collisions there is an even larger jet contribution to long-range correlations, distorting the recoil region and making the ZYAM method assumptions incorrect. To overcome this difficulty a new template fitting method was developed, where harmonic flow function is added on top of the recoil contribution measured in peripheral collisions [4]. Recently, ATLAS improved template analysis using the new pp data from collisions at 5.02 TeV measured in 2015 and re-analyzed, with a uniform method, data from collisions of pp at 13 TeV and p+Pb at 5.02 TeV [5]. The improved template method included third and fourth Fourier components in the fit, as they were found small but non-negligible, see [5]. In this analysis results for $v_{2,2}$, $v_{3,3}$ and $v_{4,4}$ amplitudes have been obtained for all three collision systems and were studied in bins of the charged-particle multiplicity, N_{ch}, and transverse momentum, p_T. In most bins, a factorization of two-particle amplitudes to single particle ones has been observed. Their variation as a function of N_{ch} and p_T is shown in Fig. 3. Comparison of results between pp collisions at 13 and 5.02 TeV reveals a very weak dependence of flow amplitudes on the collision energy and on multiplicity of events. Amplitudes in pp data at low multiplicities are very close to those in p+Pb collisions, while at higher multiplicities, p+Pb amplitudes are larger, possibly as a reflection of an increase in the number of participating nucleons in these collisions. Measured as a function of transverse momentum, the second order elliptic flow amplitudes both in pp and in p+Pb collisions behave like in Pb+Pb collisions, first increasing and then falling after reaching a maximum around $p_{\mathrm{T}} = 3$ GeV. This is confirmed further by a very good matching of amplitudes after rescaling pp data to the same maximum value measured in p+Pb collisions, as was shown in [5].

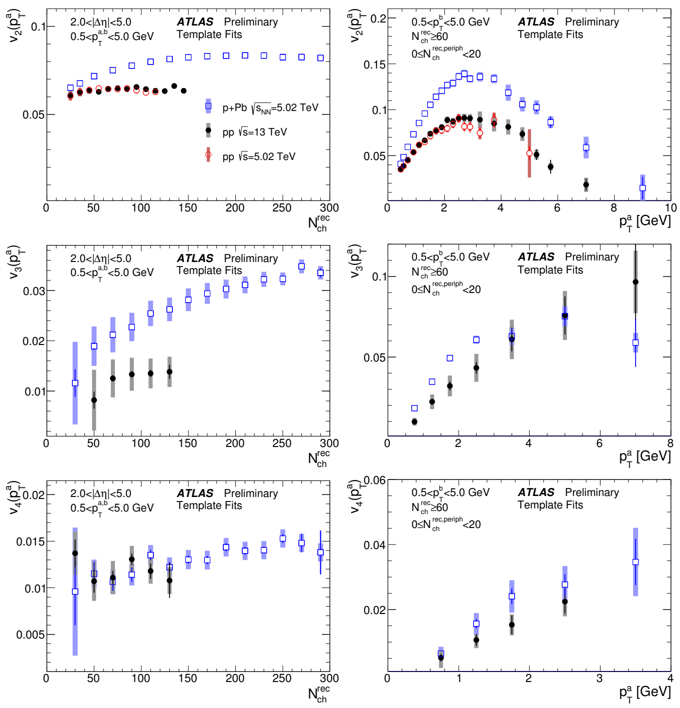

Figure 3: Comparison of $v_2 - v_4$ amplitudes obtained from the template fitting procedure on data from collisions of pp at 13 TeV, pp at 5.02 TeV, and p+Pb at 5.02 TeV, as a function of N_{ch} (left) and as a function of p_{T} (right) [5].

To complete the comparison of long-range correlations in small and large collision systems, ATLAS studied also correlations in pseudorapidity, sensitive to early-time density fluctuations in longitudinal direction [6]. This analysis has used data from Pb+Pb collisions at 2.76 TeV, p+Pb at 5.02 TeV and pp at 13 TeV. Long-range (LRC) and short-range (SRC) correlations coming from final state effects have been separated using the ratio of correlations for mixed sign pairs to same sign pairs. The magnitude of SRC correlations has been computed as an average over the two-particle pseudorapidity phase space. The variation of LRC correlations was expanded into a series of Legendre polynomials, but only the first parameter, a_1, has been found important in the series. The dependence of the expansion parameters on the charged particle multiplicity has been compared for three collision systems, Fig. 4. For short-range correlations, large differences between systems have been observed. The power-law index of the dependence has been found to decrease with the size of the system. In contrast, the magnitude of long-range correlations has been found to be similar (within 10%) in all systems, if compared at the same values of N_{ch}. This adds arguments to the conclusion that the long-range correlations in light and heavy collision systems exhibit remarkably common features.

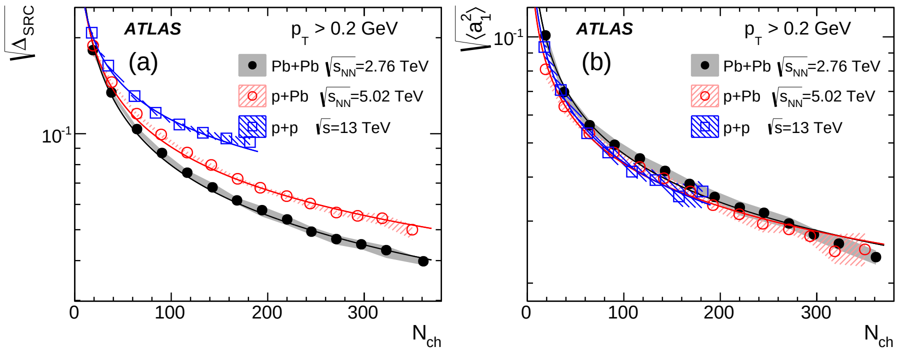

Figure 4: The magnitude of the short-range component $\sqrt{\Delta_{SRC}}$ (left) and the $\sqrt{\langle a_1^2 \rangle}$ values of a fit to long-range component dependence (right) as a function of N_{ch} for all-charge pairs in Pb+Pb (solid circles), p+Pb (open circles), and pp (open squares) collisions [6].

3. Hard probes

An important probe of the quark-gluon plasma is the production of heavy quarks. Since their masses are much larger than the maximum temperature attained in the plasma they are produced only at early times in heavy ion collisions and an interaction with QGP in the later stages of the collision modifies their properties. In case of strong interaction with QGP, high p_T heavy-quarks are expected to lose energy similarly to light quarks, so should exhibit a mass dependent production suppression. Low p_T quarks are expected to partially thermalize, and thus participate in a collective expansion, acquiring azimuthal anisotropy from interactions with the surrounding medium. ATLAS measured production of heavy quarks via their decays to muons in Pb+Pb collisions at 2.76 TeV and compared its properties to those measured in pp collisions at the same energy [7]. A signal of muons from direct quark decays has been separated from the background by a simple consistency criterion of a difference in momentum measured in two ATLAS detector subsystems, the Inner Detector and Muon Spectrometer [8]. The heavy flavor muon differential cross-sections and per-event yields have been measured in pp and Pb+Pb collisions, respectively and a ratio of these quantities, called a nuclear modification factor, R_{AA}, has been calculated as a function of p_T in different Pb+Pb collision centrality bins. Results shown in Fig. 5 indicate a significant suppression of heavy flavor production in Pb+Pb collisions with the maximum strength down to $R_{AA} = 0.4$, but without a clear p_T dependence as seen also in the suppression of production of all charged particles. It has been found also that muons from decays of heavy quarks exhibit azimuthal angle asymmetry and significant values of elliptic flow amplitudes, v_2, have been measured. Plots on the right in Fig. 5 show v_2 measured as a function of p_T for five centrality bins. The v_2 amplitudes decrease with p_T starting from $p_T = 4$ GeV and systematically decrease with increasing centrality. This behavior is again very similar to properties measured for all charged hadrons, pointing to a strong interaction between early-produced heavy quarks and the quark-gluon matter produced in heavy ion collision.

Another effect studied by ATLAS was a modification of internal structure of jets after the interaction of partons with a quark-gluon plasma created in heavy ions collisions. ATLAS measured

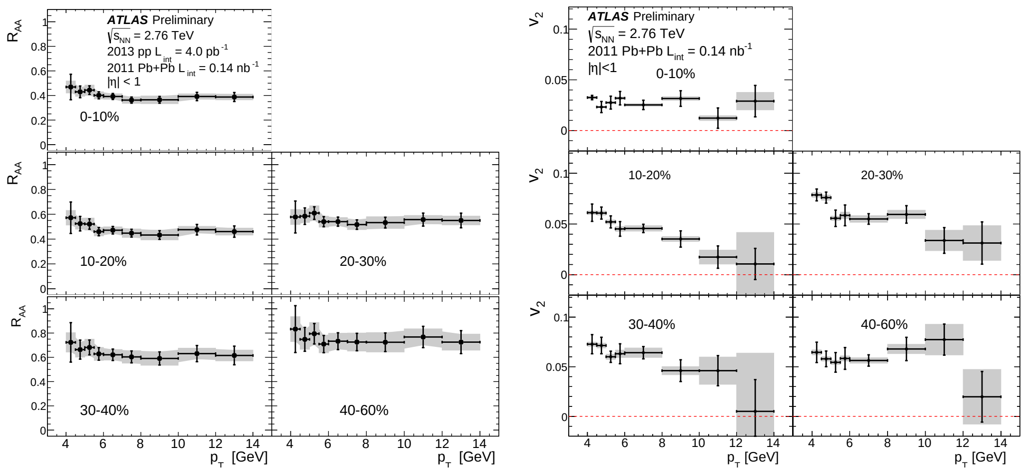

Figure 5: The heavy flavor muons, R_{AA}, suppression ratio in five centrality bins of 2.76 TeV Pb+Pb collisions (left) and the v_2 flow amplitudes (right) measured as a function of p_T [7].

jet properties in Pb+Pb collisions at 2.76 TeV and compared them with properties of jets in pp collisions, using high statistics sample of pp collisions recorded in 2013 at the same energy [9]. The modification was investigated in terms of a ratio of the distributions of the relative longitudinal momentum of tracks inside jets (z), $R_{D(z)}$, for the two collision systems. Plots of the $R_{D(z)}$ are shown in Fig. 6 in intervals of p_T in the first two rows, for central and for peripheral Pb+Pb collisions and for (0–10%) central collisions in bins of pseudorapidity in the bottom row. It is observed that in peripheral collisions jets are not modified while in the central collisions, as expected due to energy loss from interactions in QGP, there is an increase in abundance of particles at lower z values. An observed increase of the number of particles with high z values is not understood yet.

Energy loss of jets during the evolution of a collision can also be detected as an asymmetry in momenta of jets in the production of jet pairs. Such measurements were done in the past, but since not fully corrected for the energy resolution, they were difficult to compare with theoretical models. The recent ATLAS measurement [10], using Pb+Pb and pp data at a nucleon-nucleon center-of-mass energy of 2.76 TeV, is fully unfolded to the truth energy of both jet momenta. Measurements are reported for the normalized yields of the dijet asymmetry, $x_J = p_{T_2}/p_{T_1}$, with p_{T_1}, p_{T_2}, the leading and subleading jet transverse momenta, respectively and are presented as a function of p_{T_1} and collision centrality in Fig. 7. The distributions show a larger contribution of asymmetric dijet pairs in Pb+Pb data compared to that in pp data, a feature that grows stronger with centrality, consistent with the expectations of medium-induced energy loss due to jet quenching in QGP. In the $0-10\%$ centrality bin at $100 < p_{T_1} < 126$ GeV, the x_J distributions develop a significant peak at $x_J \sim 0.5$ indicating that the most probable configuration for dijets is for them to be highly imbalanced. This is in sharp contrast to the situation in the pp data where the most probable values are near $x_J \sim 1$. The centrality-dependent modifications evolve smoothly from central to peripheral collisions, and the results in the $60-80\%$ centrality bin and the pp data are generally consistent. When studied as a function of p_{T_1} it is observed that for higher leading jet momenta the differences between the x_J distribution in central Pb+Pb and the pp data become smaller. This is consistent with a picture in which the fractional energy loss decreases with jet p_T.

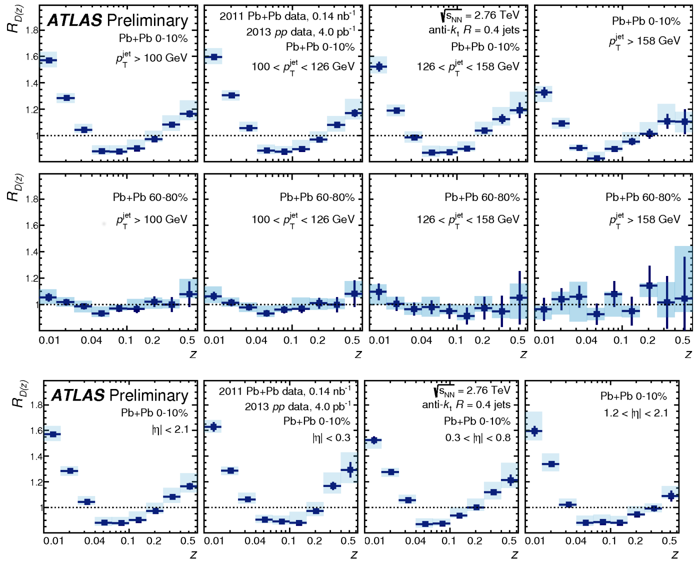

Figure 6: The ratio, $R_{D(z)}$, of the unfolded longitudinal momentum distributions of particles in jets measured in Pb+Pb collisions at 2.76 TeV to those measured in pp collisions at the same energy, shown for most peripheral and central collision bins (two upper rows) in bins of p_T and for most central collisions in bins of pseudorapidity (bottom row) [9]

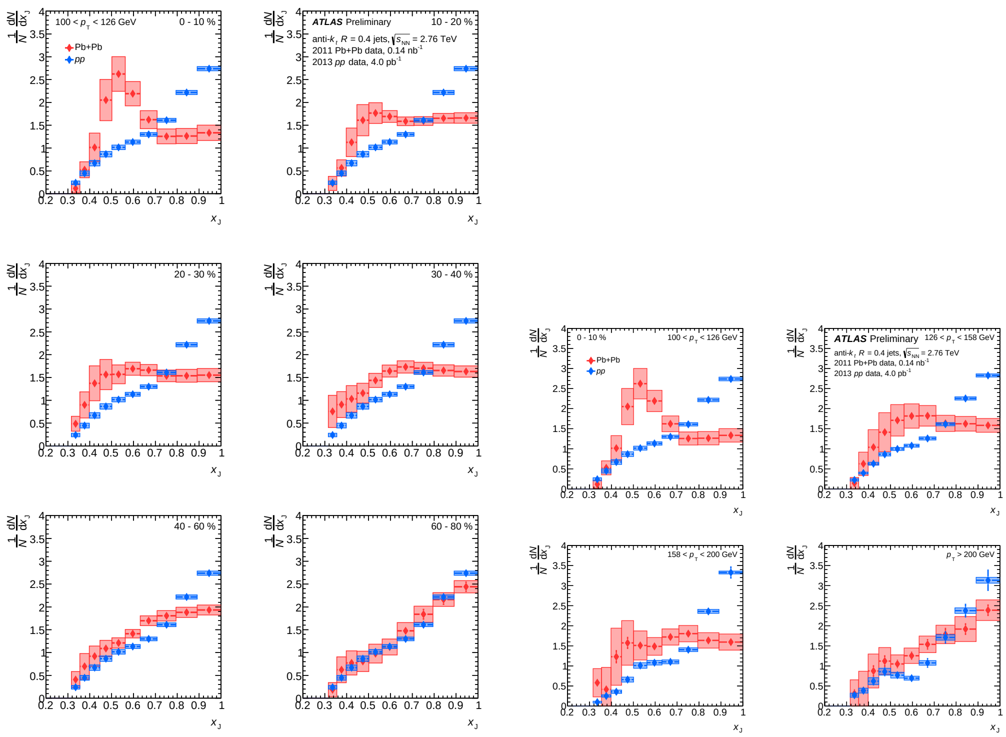

Figure 7: Comparison of distributions of the momentum balance, x_J, for jet pairs in dijet events measured in Pb+Pb (red), and in pp (blue) collisions at 2.76 TeV, in bins of centrality (left) and for $0-10\%$ central Pb+Pb collision events in bins of the leading jet transverse momentum, p_{T_1} (right) [10].

4. Summary

Recent results from the ATLAS measurements of heavy ion collisions have been focused on comparisons with lighter collision systems. In the domain of soft probes and collective effects in particle production a detailed comparison of two-particle correlations and flow properties in Pb+Pb, p+Pb and *pp* systems show many similarities which point to harmonic flow as a main source of long-range correlations in all systems. A universal behavior, with only multiplicity dependence, is also found in long-range forward-backward two-particle correlations.

A suppression in the production of heavy quarks in Pb+Pb collisions at 2.76 TeV and the v_2 flow effects seen in the distribution of their momenta similar to those in light quark production confirm that they were modified after a strong interaction with a quark-gluon matter created during the collision evolution. The effects of this interaction, which result in an energy loss of partons in jets, is also seen in the modified fragmentation of jets and in dijet asymmetry increasing with centrality and disappearing for high p_{T} jets, consistent with a picture of a parton fractional energy loss decreasing with its transverse momentum.

Acknowledgments

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