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Recent ATLAS measurements of correlations in pp and p+Pb collisions

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Recent measurements of anisotropies in the azimuthal distributions for charged particles in pp and p+Pb collisions from the ATLAS experiment at the LHC are reported. To study the impact of hard processes on the azimuthal anisotropy, the effect of particles produced in jets on the two-particle correlations in pp collisions at $\sqrt{s} = 13$ TeV is presented. For the same collision system, the elliptic flow of muons from decays of charm and bottom hadrons is also shown. Additionally, the impact of hard processes is explored with the azimuthal anisotropy of charged hadrons measured up to a high transverse momentum in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. The correlation between the mean transverse momentum and the magnitudes of the flow harmonics is reported in 5.02 TeV p+Pb collisions, aiming to investigate the role of initial conditions in the formation of azimuthal anisotropy in small systems. The measurement of elliptic flow of charged hadrons produced in photo-nuclear interactions in ultra-peripheral Pb+Pb collisions, which may help to interpret the pp and p+Pb data, is also discussed.

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1. Introduction

Significant collective effects in small systems, discovered at the Large Hadron Collider (LHC) [1, 2] and the Relativistic Heavy Ion Collider (RHIC) [3], are under extensive experimental and theoretical investigations [4]. Understanding of the new phenomena has improved significantly in recent years, but there are still open questions about the underlying mechanism, the role of hard scattering processes, and the impact of initial conditions in collisions involving light nuclei. More research is therefore needed to gain better insight into the small system collectivity.

Recent ATLAS [5] collective flow measurements in small collision systems are reported in this document. The v_n harmonics measured in 13 TeV *pp* samples of collision events with the rejected particles produced in jets are compared to that in inclusive collisions [6]. The elliptic flow of muons from decays of charm and bottom hadrons in *pp* collisions at 13 TeV [7] is also reported. For 8.16 TeV *p*+Pb collisions the azimuthal anisotropy of charged hadrons, measured up to a high transverse momentum of 50 GeV [8] is discussed. Event-by-event correlations of flow harmonics and the mean transverse momentum are expected to be sensitive to the initial conditions in nuclear collisions. The $v_n - \langle p_T \rangle$ correlation in *p*+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV is presented in this report [9]. To study the effect of initial conditions the charged hadrons elliptic flow in photo-nuclear interactions in ultra-peripheral 5.02 TeV Pb+Pb collisions is compared to the *pp* and *p*+Pb results [10].

2. Sensitivity of flow harmonics to the presence of jets in 13 TeV *pp* collisions

To get insights into the role of hard processes in the formation of azimuthal anisotropy in small systems, jets in a 13 TeV *pp* minimum bias (MB) sample with an integrated luminosity of 64 μb^{-1} are studied [6]. The two-particle correlation (2PC) method [11] is used to measure flow harmonics with the template matching procedure. To remove particles associated with jets from the 2PC analysis charged-particle tracks within $|\Delta\eta| < 1$ from the jet axis of any jet with $p_T^{jet} > 10$ GeV are rejected. The flow harmonics are obtained for four event categories selected from the MB sample using particles in 0.5–5 GeV p_T range. As a reference *Inclusive* v_n coefficients are obtained for the original MB sample, without any jet-particle rejection. The Inclusive v_n are compared with v_n obtained using the same MB sample, but with the rejection of jet-associated particles, the latter are called *AllEvents* v_n. Additionally, v_n are obtained for events without jets, referred to as *NoJet* v_n and for events containing only jets, called *WithJet* events. Figure 1 compares the multiplicity dependence of the v_2 in samples for different event categories. All v_2 values vary only weakly with multiplicity. It is observed that v_2 values in the AllEvents and NoJet samples, where particles

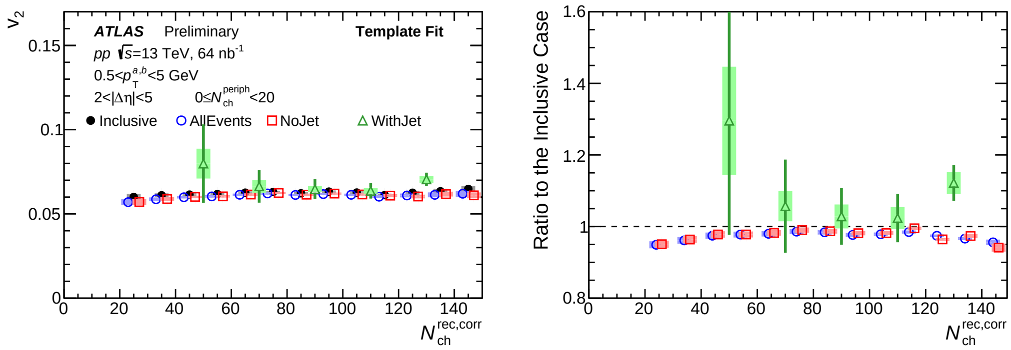

Figure 1: The left panel shows v_2 as a function of charged-particle multiplicity. The right panel shows the ratio of v_2 for the different samples to v_2 measured in the Inclusive sample [6].

associated with jets are removed, are only marginally smaller (within 2–5%) than in the Inclusive sample where no jet rejections are applied. This difference can partially arise from the softening of the p_T-spectra when removing particles associated with jets, which affects the p_T integrated v_2 in the 0.5–5 GeV p_T range. Another contribution to the observed difference in v_2 can be due to residual changes in the shape of the dijet correlations, that are not accounted for in the template fits. The results for v_2 in the WithJet sample are consistent within large uncertainties with v_2 in the Inclusive sample.

3. Heavy flavour flow in 13 TeV *pp* collisions

The elliptic flow of muons from decays of charm and bottom hadrons is measured using the 2PC method in a 13 TeV *pp* data sample of 150 pb^{-1} integrated luminosity [7]. In the analysis, the v_2 of muons from decays of charm and bottom hadrons are separated using the momentum imbalance between the tracking and muon spectrometers and specific features of the distribution of the distance-of-closest approach of muon tracks to the collision vertex. The v_2 coefficient of muons from charm and bottom decays as a function of p_T for $N_{ch}^{rec} \geq 60$ multiplicity range is shown in Figure 2. Significant v_2 harmonics are observed for muons from charm decays, while the v_2 value for muons from bottom decays is consistent with zero within uncertainties. The p_T-dependence of charm hadrons v_2 is consistent with that for light hadrons, as can be seen in Figure 2.

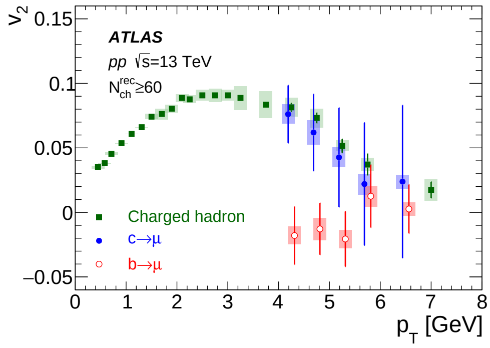

Figure 2: The v_2 of muons from charm and bottom decays as a function of p_T for $N_{ch}^{rec} \geq 60$ multiplicity range [7].

4. Azimuthal anisotropies in 8.16 TeV *p*+Pb collisions

The azimuthal anisotropy of charged particles is also measured in 8.16 TeV *p*+Pb data sample of integrated luminosity of 165 nb^{-1} using MB events, and events requiring a jet with p_T greater than either 75 GeV or 100 GeV [8]. The v_2 and v_3 harmonics are extracted using the 2PC method with the non-flow template fitting procedure [11] . The v_2 in 0–5% central *p*+Pb collisions as a function of p_T is presented in the left panel of Figure 3. In the low p_T region v_2 increases, then after a decrease for $2–3 < p_T < 9$ GeV, a plateau for high p_T ($p_T > 9$ GeV) is reached. In the p_T range 2–9 GeV, the anisotropies are larger in MB than in jet-triggered events. This effect might be attributed to the p_T-dependent relative admixture of particles from hard scattering and from the underlying event [8]. The v_2 and v_3 for $p_T < 2$ GeV were found consistent with hydrodynamic flow calculations [8]. The puzzling non-zero v_2 values in the range 9-50 GeV, shown in Figure 3 for events with jet $p_T > 100$ GeV, are not explained by the calculations based on jet quenching framework as they cannot simultaneously describe the high-p_T azimuthal anisotropy and the lack of yield suppression in *p*+Pb collisions [8]. The v_3 for $p_T \gtrsim 7$ GeV is consistent with model expectations.

5. v_n–mean p_T correlations in 5.02 TeV *p*+Pb

The modified Pearson's ρ coefficient can be used to measure the strength of the v_n–$[p_T]$ correlation [13], where $[p_T]$ denotes the mean transverse momentum of charged particles in an event. It is defined as: $\rho(v_n^2, [p_T])) = \mathrm{cov}(v_n\{2\}^2, [p_T])/(\sqrt{\mathrm{Var}(v_n\{2\}^2)_{dyn}}\sqrt{c_k})$, where in the numerator the covariance between the $v_n\{2\}^2$ and $[p_T]$ is used. To suppress non-flow effects, the

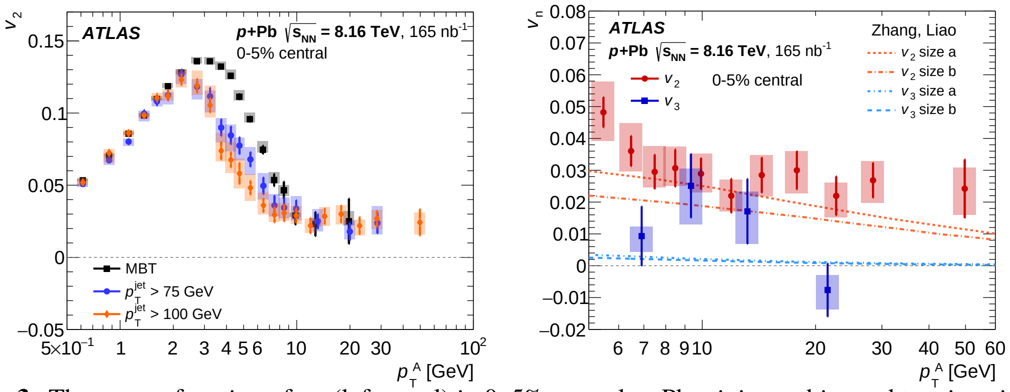

Figure 3: The v_2 as a function of p_{T} (left panel) in 0–5% central p+Pb minimum bias and two jet-triggered event samples [8]. The right panel shows v_2 and v_3 as a function of p_{T} in p+Pb events with jet $p_{\mathrm{T}} > 100$ GeV compared to theoretical predictions with two different initial geometries (denoted by a and b) [12].

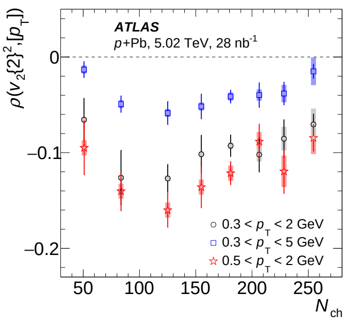

Figure 4: The modified Pearson's coefficient, $\rho(v_2^2, [p_{\mathrm{T}}])$ as a function of N_{ch} in 5.02 TeV p+Pb collisions for different p_{T} intervals [9].

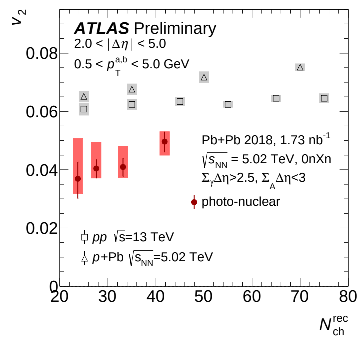

Figure 5: The elliptic flow in photo-nuclear events in 5.02 TeV Pb+Pb collisions as a function of $N_{\mathrm{ch}}^{\mathrm{rec}}$, compared to those in pp collisions at 13 TeV and p+Pb collisions at 5.02 TeV [14].

$v_{\mathrm{n}}\{2\}^2$ values are obtained using 2PC of sub-events separated by 1.5 unit in pseudorpidity, $|\eta| > 0.75$, while $[p_{\mathrm{T}}]$ is obtained using charged particles with $|\eta| < 0.5$. The denominator includes the dynamical variance of $v_n\{2\}^2$ [15] and the $[p_{\mathrm{T}}]$ variance calculated by the dynamical p_{T} fluctuation magnitude c_k [16, 17]. The ρ coefficient is obtained for the 5.02 TeV MB p+Pb and Pb+Pb data samples with an integrated luminosity of 28 nb^{-1} and 22 μb^{-1}, respectively [9] . In the Pb+Pb collisions the modified Pearson correlation coefficients for the v_2, v_3 and v_4 harmonics are measured as a function of event centrality quantified as the number of charged particles or the number of nucleons participating in the collision. The correlation coefficients for all studied harmonics exhibit a strong centrality evolution, which only weakly depends on the charged-particle momentum range. In p+Pb collisions, the modified Pearson correlation coefficient is measured for the v_2 harmonics as a function of the number of charged particles, shown in Figure 4. The measurement is performed for several intervals of the charged-particle transverse momentum. The ρ coefficient is negative and only a weak centrality dependence is observed. According to model predictions, negative values of the ρ coefficient favour a compact particle source scenario in small systems [13, 18].

6. Elliptic flow in photo-nuclear ultra-peripheral 5.02 TeV Pb+Pb collisions

A measurement of 2PC in photo-nuclear collisions is performed using a 5.02 TeV Pb+Pb data sample of integrated luminosity of 1.73 nb^{-1} [10]. Candidate photo-nuclear events are selected using a combination of signals from the zero-degree calorimeters, forward calorimeters, and the reconstructed pseudorapidity gaps constructed from calorimeter clusters and charged-particle tracks. Correlation functions are formed using charged-particle tracks in the event. A template fitting method is employed to subtract the non-flow contribution. Figure 5 shows obtained v_2 as a function of charged-particle multiplicity, $N_{\mathrm{ch}}^{\mathrm{rec}}$. Significant non-zero values of the v_2 coefficients are observed. Interestingly, the magnitude of v_2 in photo-nuclear interactions in ultra-peripheral Pb+Pb collisions is systematically lower than v_2 in *pp* and *p*+Pb collisions in similar multiplicity ranges, also presented in Figure 5.

7. Summary

The latest results of the ATLAS experiment at the LHC on collectivity in small systems were summarised in this report. The measurements provide deeper insight into the role of hard processes as well as the impact of initial conditions in collisions involving light nuclei. The presented measurements can be used to understand the underlying mechanism of QGP dynamics and constrain theoretical models.

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