

## 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  $\sqrt{s_{NN}} = 8.16$  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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\*Speaker



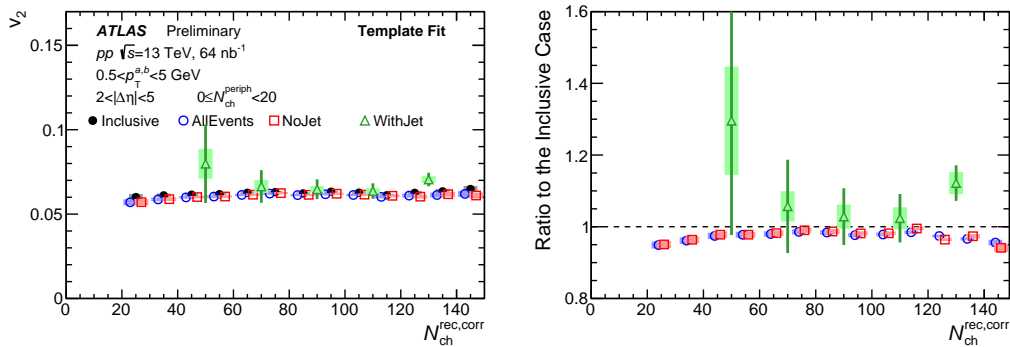
## 1. Introduction

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-to-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]. Furthermore, 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  $64 \mu\text{b}^{-1}$  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  $p_T^{\text{jet}} > 10$  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

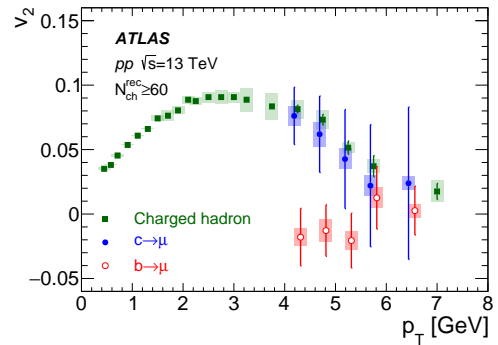


**Figure 1:** The left panel shows  $v_2$  as a function of charged-particle multiplicity. The right panel shows the ratio of  $v_2$  for the different samples to  $v_2$  measured in the Inclusive sample [6].

with multiplicity. It is observed that  $v_2$  values in the AllEvents and NoJet samples, where particles 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  $150 \text{ pb}^{-1}$  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  $N_{\text{ch}}^{\text{rec}} \geq 60$  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.



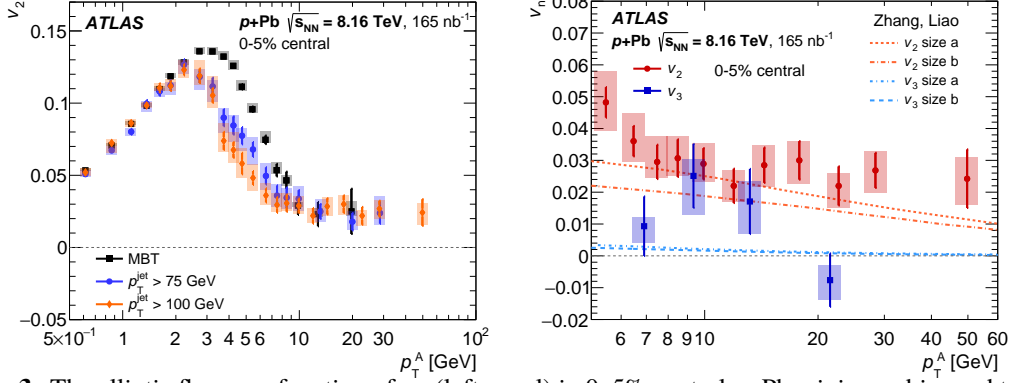
**Figure 2:** The  $v_2$  of muons from charm and bottom decays as a function of  $p_T$  for  $N_{\text{ch}}^{\text{rec}} \geq 60$  multiplicity range [7].

### 4. Azimuthal anisotropies in 8.16 TeV $p+\text{Pb}$ collisions

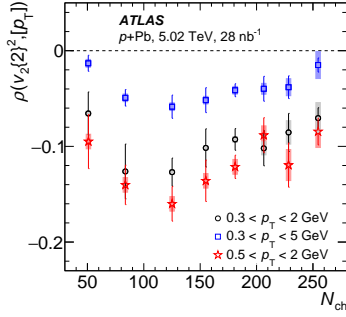
The azimuthal anisotropy of charged particles is also measured in 8.16 TeV  $p+\text{Pb}$  data sample of integrated luminosity of  $165 \text{ nb}^{-1}$  using MB events, and events requiring a jet with  $p_T$  greater than either 75 GeV or 100 GeV [8]. The  $v_2$  and  $v_3$  harmonics are extracted using the 2PC method with the non-flow template fitting procedure [11]. The  $v_2$  in 0–5% central  $p+\text{Pb}$  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  $2-3 < p_T < 9 \text{ GeV}$ , a plateau for high  $p_T$  ( $p_T > 9 \text{ GeV}$ ) 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 elliptic and triangular flow in events with the jet  $p_T > 100 \text{ GeV}$  are compared to theoretical model expectations [12]. The  $v_2$  for particles with  $p_T < 2 \text{ GeV}$  are consistent with hydrodynamic flow calculations, while the puzzling non-zero  $v_2$  values for  $p_T$  in the range 9–50 GeV are not explained. The  $v_3$  for  $p_T \gtrsim 7 \text{ GeV}$  is consistent with model expectations.

### 5. $v_n$ -mean $p_T$ correlations in 5.02 TeV $p+\text{Pb}$

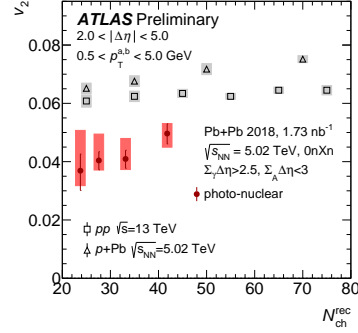
The modified Pearson’s  $\rho$  coefficient can be used to measure the strength of the  $v_n$ - $[p_T]$  correlation [13], where  $[p_T]$  denotes the mean transverse momentum of charged particles in an event. It is defined as:  $\rho(v_n\{2\}^2, [p_T]) = \text{cov}(v_n\{2\}^2, [p_T]) / (\sqrt{\text{Var}(v_n\{2\}^2)_{\text{dyn}} \sqrt{c_k}}$ , 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 elliptic flow 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 collisions compared to theoretical predictions with two different initial geometries (denoted by a and b in the legend) [12].



**Figure 4:** The modified Pearson's coefficient,  $\rho(v_2^2, [p_T])$  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  $N_{ch}^{rec}$ , compared to those in  $pp$  collisions at 13 TeV and  $p$ +Pb collisions at 5.02 TeV [14].

$v_n\{2\}^2$  values are obtained using 2PC of sub-events separated by 1.5 unit in pseudorapidity,  $|\eta| > 0.75$ , while  $[p_T]$  is obtained using charged particles with  $|\eta| < 0.5$ . The denominator includes, the dynamical variances of  $v_n\{2\}^2$  [15] and  $[p_T]$ , the latter calculated by the dynamical  $p_T$  fluctuation magnitude [16, 17]. The  $\rho$  coefficient is obtained for the 5.02 TeV MB  $p$ +Pb and Pb+Pb data samples with an integrated luminosity of  $28 \text{ nb}^{-1}$  and  $22 \mu\text{b}^{-1}$ , 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  $\rho$  coefficient is negative and only a weak centrality dependence is observed. According to model predictions, negative values of the  $\rho$  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  $1.73 \text{ nb}^{-1}$  [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,  $N_{\text{ch}}^{\text{rec}}$ . 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  $p+\text{Pb}$  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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