Abstract

The recent ATLAS results on two- and multi-particle azimuthal correlations of charged particles are presented for √s = 5.02 TeV and 13 TeV pp, √s_{NN} = 5.02 TeV p+Pb and √s_{NN} = 2.76 TeV low-multiplicity Pb+Pb collisions. To remove the “non-flow” contribution from the correlations, that arises predominantly from hard-scattering processes, a template fitting procedure is used in the two-particle correlations (2PC) measurements, while for multi-particle correlations the cumulant method is applied. The correlations are expressed in the form of Fourier harmonics v_n (n = 2, 3, 4) measuring the global azimuthal anisotropy. The measurements presented hereafter confirm the evidence for collective phenomena in p+Pb and low-multiplicity Pb+Pb collisions. For pp collisions the results on four-particle cumulants do not demonstrate a similar collective behaviour.

Keywords: Quark-gluon plasma, heavy-ion collisions, ridge, two-particle correlations, cumulants.

1. Introduction

The large azimuthal anisotropy observed in particles produced in heavy ion collisions at RHIC and LHC, is one of the main signatures of the formation of strongly interacting Quark-Gluon Plasma. Interestingly, significant long range azimuthal correlations were also observed at the LHC for the first time in pp and p+Pb collisions. This observation leads to puzzling questions related to the origin of this phenomenon as well as indicates a possible presence of the Quark-Gluon Plasma in light nuclei collisions. Since the first measurements, the collective phenomena in small systems are under extensive theoretical and experimental study. In this report, the recent ATLAS [1] results on Fourier coefficients v_n, based on a novel template fitting 2-Particle Correlation (PC) method, are shown for pp collisions at √s = 5.02 TeV and 13 TeV and p+Pb collisions at √s_{NN} = 5.02 TeV [2]. For the same systems and additionally for low-multiplicity √s_{NN} = 2.76 TeV Pb+Pb collisions measurements of multi-particle cumulants and corresponding flow harmonics are also presented [3].

2. The 2PC method

The azimuthal anisotropy in small systems is studied using the two-particle correlation function [4], which is also commonly applied to probe collective phenomena in heavy ion collisions [5]. Recently, a two-
particle correlation analysis was performed in ATLAS [2, 6] for pp collisions at \( \sqrt{s} = 2.76 \) TeV, 5.02 TeV and 13 TeV and for p+Pb collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV. The correlation function for low-multiplicity pp or p+Pb collisions, measured in the relative pseudorapidity \( (\Delta\eta) \) and azimuthal angle \( (\Delta\phi) \) of correlated particle pairs, is dominated by non-flow effects including particle pairs from the same jet, Bose-Einstein correlations, resonance decays or momentum conservation. The non-flow correlations are suppressed by requiring \( |\Delta\eta| > 2 \). The two-particle correlation function shows a sharp peak centred at \((\Delta\phi, \Delta\eta) = (0, 0)\) and a broad structure (in \( \Delta\eta \)) at \( \Delta\phi \approx \pi \). In high-multiplicity collisions, an additional long-range structure (in \( \Delta\eta \)) at \( \Delta\phi \approx 0 \), called “near-side ridge”, is clearly seen. Also the correlation function at \( \Delta\phi = \pi \) is broadened relative to the low-multiplicity collisions, revealing a presence of the “away-side ridge”. The strength of the long-range component is commonly quantified by the “per-trigger yield”, \( Y(\Delta\phi) \), which measures the average number of particle pairs associated with a trigger particle. The per-trigger yield is fitted by a template function consisting of two components: a scaled per-trigger yield for low multiplicity interactions, \( Y^{\text{perip}}(\Delta\phi) \), and an azimuthal modulation term describing the "ridge". In this approach no “ZYAM” subtraction procedure is performed on \( Y(\Delta\phi) \) or \( Y^{\text{perip}}(\Delta\phi) \) [2]. The azimuthal modulation parameters \( v_{n,\eta} \) obtained from the fitting procedure were found to factorize into a product of single particle flow harmonics \( v_n \), hence \( v_n = \sqrt{v_{n,\eta}} \).

One can see that all three \( v_n \) harmonics in 5.02 and 13 TeV pp data are \( N_{\text{ch}} \)-independent, while the p+Pb \( v_2 \), \( v_3 \) and \( v_4 \) increase with increasing \( N_{\text{ch}} \). The \( p_T \)-dependence of \( v_n \) in 5.02 and 13 TeV pp, and 5.02 TeV p+Pb collisions for \( N_{\text{ch}} \geq 60 \) is also shown in Fig. 1 (the right column). Similar \( v_2 \) harmonics are observed in pp collisions at both collision energies. As a function of \( p_T \), \( v_2 \) harmonics rise reaching a maximum near 3 GeV and then they drop, reaching almost 0 at \( p_T \approx 7 \) GeV. In p+Pb collisions a more rapid increase of \( v_2 \) is measured, but generally a similar trend is observed in both systems. The \( v_3 \) harmonic in 13 TeV pp increases with \( p_T \) over the measured \( p_T \) range. For p+Pb collisions, larger \( v_3 \) values are observed than in pp for \( p_T < 3 \) GeV. At higher \( p_T \), \( v_3 \) in p+Pb data saturates. The \( v_4 \) in 13 TeV pp and 5.02 TeV p+Pb collisions increases with \( p_T \) and larger \( v_4 \) values are measured in p+Pb collisions than in pp data.

### 3. Multi-particle cumulants

The multi-particle cumulant method of measuring flow harmonics [7, 8] is a commonly used approach, which efficiently suppresses the non-flow correlations. In the first step of the cumulant method, the 2k-particle azimuthal correlations, \( \text{corr}_{n}(2k) \), are calculated. Then, the multi-particle cumulants \( c_n(2k) \) are obtained by subtracting from \( \text{corr}_{n}(2k) \) all correlations between fewer number of particles, which include most of non-flow correlations. The cumulant method was used for Pb+Pb [9] and p+Pb collisions [10].

![Figure 1](https://example.com/figure1.png)
and recently, for \(pp\) collisions [11]. In this report, the ATLAS measurements of multi-particle cumulants are presented for \(pp\) collisions at \(\sqrt{s} = 5.02\) TeV and 13 TeV, for \(\sqrt{s_{NN}} = 5.02\) TeV \(p+Pb\) and for low-multiplicity \(p+Pb\) collisions at \(\sqrt{s_{NN}} = 2.76\) TeV [3]. Cumulants are calculated in unit-size bins in the number of reference particles, \(M_{\text{ref}}\), which is the number of reconstructed charged-particles with \(|\eta| < 2.5\) and with \(p_T\) ranges: \(0.3 < p_T < 3\) GeV or \(0.5 < p_T < 5\) GeV. It means that cumulants are calculated for events selected with a fixed number of \(M_{\text{ref}}\) (called \(\text{EvSel}_M\) selection). The cumulants are then calculated in broader, statistically significant multiplicity intervals by averaging with weights accounting for the event trigger efficiency and the number of 2k-multiplets. Results obtained for different collision systems or \(p_T\)-ranges are compared in a common event activity variable defined as the mean number of charged particles with \(p_T > 0.4\) GeV in events in the \(M_{\text{ref}}\) interval used for the cumulants calculations. The results on four-

Figure 2: The second order cumulant \(c_2(4)\) obtained from four-particle correlations as a function of \((N_{ch}(p_T > 0.4\text{GeV}))\) for \(pp\) collisions at \(\sqrt{s} = 5.02\) and 13 TeV, \(p+Pb\) collisions at \(\sqrt{s_{NN}} = 5.02\) TeV and \(Pb+Pb\) collisions at \(\sqrt{s_{NN}} = 2.76\) TeV [3].

Figure 3: Comparison of \(v_2(2,|\Delta\eta| > 2), v_2(4), v_2(6)\) and \(v_2(8)\) as a function of \((N_{ch}(p_T > 0.4\text{GeV}))\) for \(\sqrt{s_{NN}} = 5.02\) TeV \(p+Pb\) collisions and \(\sqrt{s_{NN}} = 2.76\) TeV \(Pb+Pb\) collisions. The results are presented for particles with \(0.3 < p_T < 3\text{GeV}[3]\).
multiplicity and transverse momentum. The measurement shows that $v_2$ in $pp$ collisions weakly depends on multiplicity and collision energy. The $p+Pb$ $v_2$ values are larger than the $pp$ $v_2$ for all multiplicities and are observed to increase with $N_{ch}$. As a function of $p_T$, the $p+Pb$ $v_2$ is larger than $v_2$ in $pp$ collisions but similar $p_T$ dependence is observed, which also resembles the trend seen in $Pb+Pb$ collisions.

Multi-particle cumulants were measured for the same $pp$ and $p+Pb$ collision systems as well as in low-multiplicity $Pb+Pb$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The collective nature of multi-particle correlations is well confirmed for $p+Pb$ and $Pb+Pb$ collisions for charged-particle multiplicities above 100. For $pp$ collisions, the four-particle cumulants are positive or consistent with zero over the full range of particle multiplicities. Therefore, these measurements in $pp$ collisions, do not satisfy the requirement of being negative, indicating that $c_2[4]$ cumulants may still be biased by residual non-flow correlations. It should be noted that, to estimate and limit the effect of non-flow correlations, ATLAS has recently proposed a novel sub-event cumulant method [12], in which particles from different sub-events separated in pseudorapidity are used for cumulant calculations.

The measured $v_2$ harmonics from multi-particle cumulants have larger values for Pb+Pb collisions as compared to $p+Pb$ collisions and for each system $v_2[2k]$ are similar for $k = 2, 3$ and 4, while $v_2[2, |\Delta\eta| > 2]$ is systematically larger than the second order Fourier component calculated with more than two-particle cumulants. This observation is consistent with models assuming fluctuation-driven initial-state anisotropies.

Interestingly, the $c_3[2, |\Delta\eta| > 2]$ for reference particles with $0.3 < p_T < 3$ GeV, and the corresponding $v_3[2, |\Delta\eta| > 2]$ harmonics are comparable for Pb+Pb and $p+Pb$ collisions, while the fourth order cumulants, $c_4[2, |\Delta\eta| > 2]$, for the $pp$ data are comparable to that for $p+Pb$ and Pb+Pb collisions in the overlapping range of $N_{ch}$.

The results on two- and multi-particle correlations presented in this note provide significant insights into the understanding of azimuthal angle anisotropies in small collision systems and provide useful constraints on the theoretical modelling.

This work was supported in part by the National Science Centre, Poland grant 2015/18/M/ST2/00087 and by PL-Grid Infrastructure.

References

[1] ATLAS Collaboration, JINST 3 (2008) S08003.
[2] ATLAS Collaboration, arXiv:1609.06213 [nucl-ex].
[3] ATLAS Collaboration, ATLAS-CONF-2016-007, 2016, url: http://cdsweb.cern.ch/record/1624013.
[4] ATLAS Collaboration, Phys. Rev. Lett. 110 (2013) 182302, arXiv:1212.5198 [hep-ex].
[5] ATLAS Collaboration, Phys. Rev. C 86 (2012) 014907, arXiv:1203.3087 [hep-ex].
[6] ATLAS Collaboration, Phys. Rev. Lett. 116 (2016) 172301, arXiv:1509.04776 [hep-ex].
[7] N. Borghini, P. M. Dinh and J. Y. Ollitrault, Phys. Rev. C 63 (2001) 054906.
[8] A. Bilandzic, R. Snellings and S. Voloshin, Phys. Rev. C 83 (2011) 044913, arXiv:1010.0233 [nucl-ex].
[9] ATLAS Collaboration, Eur. Phys. J. C 74 (2014) 3157, arXiv:1408.4342 [hep-ex].
[10] ATLAS Collaboration, Phys. Lett. B 725 (2013) 60, arXiv:1303.2084 [hep-ex].
[11] CMS Collaboration, Phys. Lett. B 765 (2017) 193, arXiv:1606.06198 [nucl-ex].
[12] ATLAS Collaboration, ATLAS-CONF-2013-104, 2013, url: http://cdsweb.cern.ch/record/1624013.