Azimuthal anisotropies in Pb+Pb and p +Pb collisions with the ATLAS detector

Barbara Wosiek*

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

for the ATLAS Collaboration

Abstract

An overview of the results on anisotropic particle flow in lead-lead collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and proton-lead collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV obtained with the ATLAS detector at the Large Hadron Collider is presented. The final-state anisotropy is studied by measuring the Fourier harmonics (v_n) of the azimuthal angle distributions of produced charged particles. A large anisotropy in the azimuthal angle distribution of particles produced in Pb+Pb collisions is measured, providing new constraints on the initial geometry models and on hydrodynamic evolution of the system. The same analysis methods have been also applied to study modulations in the azimuthal angle distributions of particles produced in p +Pb collisions. The obtained results are indicative of the importance of final-state effects in small collision systems which may lead to collective flow similar to that observed in the dense and hot system created in Pb+Pb collisions.

Keywords: heavy-ion collisions, quark-gluon plasma, collective flow, long-range correlations

1. Introduction

The azimuthal anisotropy of particle emission in the transverse plane is a powerful tool to study properties of the dense, hot matter created in ultra-relativistic heavy-ion collisions [1, 2]. This anisotropy results from the pressure-driven expansion of the system, with asymmetric pressure gradients generated due to the initial spatial asymmetry of the collision zone. It is described by Fourier analysis of the particle distribution in azimuthal angle ϕ :

$$E \frac{d^3 N}{dp^3} = \frac{1}{p_T} \frac{d^3 N}{d\phi dp_T dy} = \frac{1}{2\pi p_T} \frac{E}{p} \frac{d^2 N}{dp_T d\eta} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\phi - \Phi_n)] \right), \quad (1)$$

where v_n is the n -th order flow harmonics, and Φ_n , referred to as the event plane angle, measures the direction of the collective particle flow. The v_n harmonic is calculated according to the formula $v_n = \langle \cos(n(\phi - \Phi_n)) \rangle$, while Φ_n is determined using azimuthal correlations between the produced particles [2]. Different analysis methods can be applied to measure flow harmonics.

*Corresponding author. Tel.: +48 12 6628429

Email address: barbara.wosiek@ifj.edu.pl (Barbara Wosiek)

Preprint submitted to *Annals of Physics*

November 26, 2013

The most commonly used is the event-plane method (EP), as described above. Another method (2PC) allows to extract v_n coefficients from two-particle azimuthal correlations using the mixed events technique [3]. However, both EP and 2PC methods are potentially sensitive to non-flow correlations, not related to the initial geometry, which can result e.g. from resonance decays, jet production, quantum interference or energy-momentum conservation. In order to suppress non-flow contributions, the multi-particle cumulant methods [4–7] can be used which make it possible to eliminate the correlations between k particles using $2k$ -particle cumulants.

The anisotropy of charged particle azimuthal angle distributions in heavy-ion collisions has been a subject of extensive experimental studies at RHIC [8–13] and recently also at the LHC [14–24]. In non-central heavy-ion collisions, the large and dominating v_2 coefficient is mainly associated with the elliptic shape of the nuclear overlap. The v_2 coefficient in central collisions and other v_n coefficients in all collisions are related to various geometric configurations arising from fluctuations of the nucleon positions in the overlap region [25]. The reported results are consistent with model calculations based on hydrodynamic description of the system evolution and provide conclusive evidence that the created hot and dense matter produced in these collisions behaves collectively and has properties resembling those of a nearly perfect fluid [26].

In p +A collisions, the size of the produced system is small as compared to the mean free path of its constituents. Therefore, it might be expected that weaker collective flow, if any, is generated in p +A collisions as compared to heavy-ion interactions. Contrary to these expectations, the recently measured Fourier harmonics, v_2 and v_3 for p +Pb collisions at the LHC energy of $\sqrt{s_{NN}} = 5.02$ TeV [27–31], show signals comparable in magnitude to these obtained in Pb+Pb collisions. A variety of models has been proposed to explain the measurement of long-range correlations in p +Pb collisions [32–43]. A remarkable agreement is shown with the viscous hydrodynamic model [42, 43], although its applicability, as noted above, can be questioned. Some of the experimental observations are also well reproduced by the initial-state model with the saturation of the parton distribution in the Pb nucleus [33].

In this report, the ATLAS measurements of the azimuthal anisotropy in Pb+Pb and p +Pb collisions are reviewed.

2. Heavy-ion collisions with the ATLAS detector

The results presented here are based on the analysis of minimum-bias Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded by ATLAS in 2010 and corresponding to an integrated luminosity of approximately $7 \mu\text{b}^{-1}$. The p +Pb measurements were performed using the minimum-bias data sample collected during the short run in 2012 with the integrated luminosity of about $1 \mu\text{b}^{-1}$.

The measurements were performed using the ATLAS inner detector, forward calorimeters, trigger and data acquisition systems [44]. The inner detector, placed in a 2 T solenoid, provides precise determination of charged particles momenta over a pseudorapidity range out to $|\eta| = 2.5$ and over the full range in the azimuth. The finely segmented calorimeter allows for measurements of hadronic and electromagnetic energy deposits over $|\eta| < 4.9$. The calorimeter also features a complete coverage in the azimuth. A Level 1 trigger system was used to record minimum bias collisions. It required the coincidences of signals recorded in both zero-degree calorimeters (ZDC), located symmetrically at $z = \pm 140$ m, and in the minimum-bias trigger scintillator counters (MBTS) at $z = \pm 3.6$ m. Additional offline event selections are applied to reduce non-collisional backgrounds, electromagnetic processes, and pile-up interactions. The analyzed samples consist of about 40×10^6 and 2×10^6 events for Pb+Pb and p +Pb collisions, respectively.

The summed transverse energy, ΣE_T^{FCal} , measured in the ATLAS forward calorimeters covering $3.2 < |\eta| < 4.9$ was used to define the centrality of the Pb+Pb collision (for more details see [18]). The ΣE_T^{FCal} distribution was divided into centrality intervals, each representing a percentile fraction of all events after accounting for 2% inefficiency in recording most of the peripheral collisions. For each centrality interval, a standard Glauber Monte Carlo model [45, 46] is used to estimate the average number of participating nucleons, $\langle N_{\text{part}} \rangle$, which provides an alternate measure of the collision centrality. For asymmetric p +Pb collisions, centrality is defined using the sum of transverse energies measured in the FCal with $3.2 < \eta < 4.9$ in the direction of the Pb beam, ΣE_T^{Pb} [27]. Figure 1 shows the distributions of ΣE_T^{FCal} for Pb+Pb collisions (left plot) and ΣE_T^{Pb} for p +Pb events (right plot).

Figure 1: (left) ΣE_T^{FCal} distribution divided into 10% centrality intervals (black) for Pb+Pb collisions [18]. Proton-proton data at $\sqrt{s} = 2.76$ TeV, convolved with a Glauber Monte Carlo calculation is shown by grey histogram. (right) Distribution of ΣE_T^{Pb} for minimum-bias p +Pb events [27]. Vertical lines indicate the boundaries of the event centrality classes. Shaded bands indicate the larger peripheral and central intervals having $\Sigma E_T^{\text{Pb}} < 20$ GeV and $\Sigma E_T^{\text{Pb}} > 80$ GeV, respectively.

Monte Carlo (MC) samples were used in the analysis to determine tracking efficiencies and rates of fake tracks. The HIJING event generator [47] was used to produce minimum-bias lead-lead collisions. The events were generated with the default parameters, except for the jet quenching which was turned off. The azimuthal anisotropy was introduced into the HIJING at the generator level by changing the azimuthal angle of each particle [8] in order to get the anisotropic azimuthal angle distribution consistent with ATLAS v_n ($n = 2, 3, \dots, 6$) measurements [18, 19]. The tracking efficiency for p +Pb collisions was evaluated also using HIJING-generated p +Pb events without any collective flow effects implemented. The detector response was simulated using the GEANT4 package [48] with conditions corresponding to those of the 2010 Pb+Pb and 2012 p +Pb run respectively. The simulated events are reconstructed in the same way as the data.

The precision silicon tracking detectors consisting of pixel detectors and a semiconductor microstrip tracker (SCT) were used to reconstruct charged particle trajectories with a minimum p_T of 0.5 GeV for Pb+Pb collisions. The tracking efficiency is found to weakly depend on the collision centrality. For the lowest transverse momenta (0.5–0.6 GeV), the efficiency at mid-rapidity is of the order of 50% and falls to about 30% at high $|\eta|$. For higher transverse momenta it reaches about 70% at mid-rapidity and drops to about 50% at high $|\eta|$. The fake rate is below 1% over a wide range of collision centrality and p_T . Only for the most central collisions, the fake rate for the lowest transverse momenta is higher, i.e. of the order of a few percent. For p +Pb collisions, charged particles are reconstructed down to p_T of 0.3 GeV. The efficiency is found to depend only weakly on the event multiplicity and on p_T for transverse momenta above 0.5 GeV. An efficiency of about 82% is observed at mid-rapidity, $|\eta| < 1$, decreasing to about

68% at $|\eta| > 2$. For low- p_T tracks, between 0.3 GeV and 0.5 GeV, the efficiency ranges from 74% at $\eta = 0$ to about 50% for $|\eta| > 2$.

3. Collective flow measurements in Pb+Pb collisions

Figure 2: Transverse momentum dependence of v_n harmonics for several centrality intervals [19]. The shaded bands indicate the systematic uncertainties.

The final-state anisotropy is studied by measuring the Fourier harmonics (v_n) of the azimuthal angle distributions of produced charged particles. The second harmonic, v_2 , is directly related to the elliptic shape of the overlap region while higher order harmonics are sensitive to fluctuations in the initial spatial deformations. In ATLAS, flow harmonics have been measured with the event plane method [18, 19], with two-particle correlations [19] and with two- and four-particle

cumulants [49]. Transverse momentum dependence of flow harmonics, v_n , $n = 2 - 6$, obtained with the event plane method, is shown in Fig. 2. It can be seen that in lead-lead collisions, the final-state anisotropy is dominated by the second harmonic, v_2 , for all but the most central 0–5% centrality interval [18, 19]. As expected, v_2 shows a strong centrality dependence. Higher order harmonics ($n > 2$) as well as the first order harmonic, v_1 , were found to also contribute to the measured anisotropy [19]. It has to be noted that the measurements shown in Fig. 2 are well described by the viscous hydrodynamic models, which include an advanced modeling of the initial state [50–52].

The two-particle correlation study in Pb+Pb collisions [19] revealed the presence of long-range correlations, extended over a broad range in relative difference in pseudorapidity between particles forming a pair, $\Delta\eta$, while confined in $\Delta\phi$. This complex structure in the two-particle correlation function is found to be well reproduced at low transverse momenta by the combination of the contributions of $v_1 - v_6$ flow harmonics, indicating that this structure is dominated by collective particle flow.

The observed large magnitudes of the odd flow harmonics imply the presence of significant fluctuations in initial geometry due to fluctuating nucleon positions in the overlap region. Fluctuations in the initial geometry should induce correlations between the symmetry planes of different orders, Φ_n . Such correlations have been indeed observed [53]. Figure 3 shows centrality dependence of several two-plane correlators, defined as $\langle \cos k(\Phi_n - \Phi_m) \rangle$. It was found that they can be partially attributed to the fluctuations of the initial geometry, but are also generated during the system evolution, implying the presence of non-linear effects in the hydrodynamic description of the system evolution [54, 55].

Figure 3: Eight two-plane correlators $\langle \cos k(\Phi_n - \Phi_m) \rangle$ as a function of N_{part} [53]. The error bars and shaded bands indicate the statistical uncertainty and total systematic uncertainty, respectively.

Additional insight into the initial geometry fluctuations can be provided by studying fluctuations of the flow harmonics. A novel technique has been developed for direct measurements of flow harmonic fluctuations, which is based on the event-by-event determination of v_n harmonics. The measured v_n distributions are unfolded for the variation in the event multiplicity [20]. Figure 4 shows the event-by-event distributions of v_n for $n = 2, 3$ and 4 for different

Pb+Pb collision centralities. It can be seen that v_3 and v_4 are well described by the projection of the two-dimensional Gaussian distributions (shown by solid curves in Fig. 4), indicating that they result from random fluctuations in the initial geometry. In the case of the second flow harmonic, a similar consistency with Gaussian fluctuations is observed only in the most central, (0–2) % collisions. From the measured v_n distributions, relative fluctuations of flow harmonics, $\langle v_n \rangle / \sigma_{v_n}$, are derived and compared to the initial state eccentricity fluctuations predicted by the Glauber [45] and KLN [56] Monte Carlo models. It is shown that neither of the initial-state models can consistently describe the measured v_n distributions, see Fig. 5.

Figure 4: The event-by-event v_n distributions for different centrality intervals for $n = 2$ (left panel), $n = 3$ (middle panel) and $n = 4$ (right panel) [20]. The bars denote statistical errors, and the shaded bands show uncertainties on the shape of v_n distributions.

4. Azimuthal anisotropy in p +Pb collisions

The two-particle correlation function, $C(\Delta\phi, \Delta\eta)$, measured in p +Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [27], showed a striking similarity to the $C(\Delta\phi, \Delta\eta)$ obtained for Pb+Pb collisions. Therefore, it is interesting to see whether it can also be described by contributions of collective flow harmonics, as it was the case for the Pb+Pb collision system. Figure 6 shows the two-dimensional correlation function measured for charged particles in peripheral ($\Sigma E_T^{\text{Pb}} < 20$ GeV) and central ($\Sigma E_T^{\text{Pb}} > 80$ GeV) p +Pb collisions. A strong correlation is seen at $\Delta\phi \approx 0$ and $\Delta\eta \approx 0$ due to charged particles coming from the same jet or high- p_T resonances, and a weaker correlation at $\Delta\phi \approx \pi$ due to particles recoiling against jets or contributing to the momentum conservation. For central collisions, underneath the sharp jet peak, there is an interesting long-range correlation extended in $\Delta\eta$ over more than eight pseudorapidity units (commonly called the ridge). This near-side long-range correlation structure is practically absent in peripheral collisions. The recoil component ($\Delta\phi \approx \pi$) in central p +Pb collisions is broader than in peripheral collisions, consistent with the presence of a long-range correlation component also on the away-side.

To further investigate these long-range correlations, the analysis is restricted to particle pairs with $2 < |\Delta\eta| < 5$, thus eliminating short-range correlations. The strength of the long-range correlation is quantified by the per-trigger yield function, $Y(|\Delta\phi|)$, which measures the correlation between two particles in a restricted $\Delta\eta$ range at a given $|\Delta\phi|$. Its minimum value is fixed to zero by subtracting a value of the ZYAM-determined [57] pedestal level. The distributions of $Y(|\Delta\phi|)$ are shown in Fig. 7 for different ranges in p_T^a and over a full measured range in p_T^b (with

Figure 5: The $\langle N_{\text{part}} \rangle$ dependence of $\langle v_n \rangle$ (left panels), σ_{v_n} (middle panels) and $\sigma_{v_n} / \langle v_n \rangle$ (right panels) for $n = 2$ (top row), $n = 3$ (middle row) and $n = 4$ (bottom row) [20]. Each panel shows the results for three p_T ranges together with the total systematic uncertainties. The dotted lines in the right column indicate the value $\sqrt{4/\pi - 1}$ expected for the radial projection of a 2D Gaussian distribution centered around origin. The relative flow fluctuations are compared with the relative initial eccentricity fluctuations given by the Glauber model [45] and MC-KLN model [56].

Figure 6: Two-dimensional correlation functions for (a) peripheral and (b) central p +Pb collision events, both truncated at a maximum to suppress strong correlations at $(\Delta\phi, \Delta\eta) = (0, 0)$ [27].

indices a and b denoting particles forming a pair) for central and peripheral collisions. For central collisions the per-trigger yield shows the near-side and away-side peaks, with larger magnitude on the away-side. In peripheral collisions there is only the away-side peak interpreted as the recoil component. The difference ΔY between central and peripheral events, which measures the correlation after the recoil subtraction, is also shown in Fig. 7. It can be seen that the subtraction

of the recoil component has no effect on the near-side, but is important on the away-side. As a result, ΔY is symmetric around $|\Delta\phi| = \pi/2$, consistent with the typical flow-like modulation as illustrated by the functions $a_0 + 2a_2 \cos 2\Delta\phi$ and $a_0 + 2a_2 \cos 2\Delta\phi + 2a_3 \cos 3\Delta\phi$ (marked with solid and dashed curves respectively) obtained by a Fourier decomposition of $\Delta Y(|\Delta\phi|)$ with coefficients $a_n = \langle \Delta Y(|\Delta\phi|) \cos n|\Delta\phi| \rangle$.

Figure 7: Distributions of per-trigger yield in the peripheral and the central p +Pb collision events activity classes and their differences (solid symbols). Overlaid are functions $a_0 + 2a_2 \cos 2\Delta\phi$ (solid line) and $a_0 + 2a_2 \cos 2\Delta\phi + 2a_3 \cos 3\Delta\phi$ (dashed line) [27].

The integrated per-trigger yield Y_{int} is obtained by integrating the per-trigger yields over the near-side ($|\Delta\phi| < \pi/3$) and away-side ($2\pi/3 < |\Delta\phi| < \pi$). Y_{int} is shown in Fig. 8 as a function of p_T^a for four centrality intervals. Bottom plots show the difference, ΔY_{int} obtained by subtracting the integrated yield measured in the most peripheral collisions ($\Sigma E_T^{\text{Pb}} < 20$ GeV). One can see that after subtraction of the integrated yield measured for the most peripheral centrality interval, the transverse momentum dependence on the near-side and away-side is the same in all other centrality intervals.

The relative amplitudes, c_n , of the $\cos n\Delta\phi$ modulation of $\Delta Y(|\Delta\phi|)$, can be estimated using the coefficients a_n and correcting for the corresponding pedestal levels ($c_n = a_n/(a_0 + b_{\text{ZYAM}})$). These c_n amplitudes are equivalent to $v_{n,n}$ coefficients determined from the Fourier analysis of two-particle correlations in Pb+Pb collisions. They can be converted to the single-particle level modulation, $v_n\{2PC\}$ (denoted here as s_n), assuming the factorization relation. The extracted

Figure 8: Integrated per-trigger yields as a function of p_T^a in various ΣE_T^{Pb} intervals on the near-side (top left) and away-side (top right) [27]. The bottom panels show the difference ΔY_{int} obtained after subtracting the integrated yield in the $\Sigma E_T^{\text{Pb}} < 20$ GeV event class. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively.

amplitudes, c_n and s_n for $n = 2, 3$ are shown in Fig. 9 as a function of p_T^a in various ΣE_T^{Pb} intervals. Large magnitude of s_2 can be observed, reaching 0.1 at p_T of about 3 GeV, comparable to the v_2 magnitude measured in Pb+Pb collisions (see Fig. 2). Furthermore, the p_T behavior is also similar to that seen for the Pb+Pb collision system showing the typical dependence expected from the hydrodynamic evolution of the system. Amplitudes s_3 are smaller as compared to s_2 , and also consistent with the Pb+Pb data.

To further investigate this surprising collective-like nature of long-range correlations in p+Pb collisions, a complementary analysis has been performed, aimed to directly determine the v_2 coefficient using the cumulant method [28]. Transverse momentum dependence of $v_2\{2\}$ and $v_2\{4\}$, obtained with two- and four-particle cumulants respectively is shown in Fig. 10. The two-particle cumulant method provides systematically overestimated v_2 values due to the dominant contribution of non-flow correlations. The results of the four-particle cumulants, with eliminated non-flow effects, show a clear v_2 signal. As a function of transverse momentum the second-order harmonic, $v_2\{4\}$, increases with p_T up to 2–3 GeV, and is compatible with the discussed above measurements of $v_2\{2PC\}$ obtained from the analysis of the two-particle correlation function accounting for particle pairs with $2 < |\Delta\eta| < 5$.

A similar consistency of $v_2\{4\}$ and $v_2\{2PC\}$ is also observed for the v_2 coefficient integrated over p_T for p+Pb collisions with large ΣE_T^{Pb} (see left panel of Fig. 11). For lower ΣE_T^{Pb} , the observed disagreement could be due either to the subtraction procedure used to derive $v_2\{2PC\}$ or to residual non-flow effects in $v_2\{4\}$ or to a combination of both. Interestingly, the measured v_2 is in a remarkable agreement with predictions of the viscous hydrodynamic model [43]. This

Figure 9: The c_n (left) and s_n (right) vs p_T^a in various ΣE_T^{Pb} intervals [27]. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively.

Figure 10: The v_2 flow coefficient calculated with the two-particle (circles) and four-particle (stars) cumulants as a function of transverse momentum in four different centrality intervals [28]. Bars denote statistical errors; systematic uncertainties are shown as shaded bands. The v_2 derived from the Fourier decomposition of two-particle correlations is shown by open squares.

agreement indicates the importance of final-state effects in p +Pb collisions. There are other alternative explanations which can describe the measurements as due to the initial-state effects, such as the saturation of the gluon distribution function [33].

Finally, the right panel of Fig. 11 shows the comparison of v_2 measured in p +Pb data, either with the four-particle cumulant method or with the two-particle correlation method to the v_2 obtained with the event-plane method for central and peripheral Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The v_2 measurements for the p +Pb collision system fall in between the results for

Figure 11: (left) The second-order harmonic, v_2 , integrated over p_T and η , calculated with two- and four-particle cumulants (circles and stars, respectively), as a function of ΣE_T^{Pb} [28]. Systematic uncertainties are shown as shaded bands. Also shown is $v_2\{2PC\}$ (squares) and predictions from the hydrodynamic model (triangles) for the same selection of charged particles as in the data. (right) Comparison of the transverse momentum dependence of the v_2 coefficient measured in p +Pb collisions with the four-particle cumulants $v_2\{4\}$, and with the two-particle correlation method $v_2\{2PC\}$ to v_2 obtained with the event-plane method for central and peripheral Pb+Pb collisions [28]. Systematic uncertainties are shown as shaded bands.

central and peripheral Pb+Pb collisions.

5. Summary

A systematic and detailed study of the azimuthal anisotropies has been performed by the ATLAS, ALICE and CMS experiments for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The obtained multitude of high-precision measurements shows a remarkable agreement with calculations based on the viscous hydrodynamic description of the system evolution which includes an advanced modeling of the initial state geometric configuration and its fluctuations. This non-trivial applicability of hydrodynamics requires a short mean free path of system constituents as compared to the system size and clearly shows that the created matter is strongly coupled and exhibits a collective behavior. In the case of p +Pb collisions, the size of the produced system is small as compared to the mean free path of its constituents. Therefore, one can expect weaker, if

any, collective flow, and furthermore the applicability of hydrodynamic description is problematic. Yet, the LHC measurements of long-range correlations in p +Pb collisions show intriguing similarities to the Pb+Pb results, suggesting the presence of collective flow in p +Pb collisions. The differing theoretical explanations of the p +Pb results are still being hotly debated. Further measurements and more detailed theoretical studies are necessary to better understand the properties of both the cold nuclear matter formed in p +Pb collisions and the hot and dense matter created in Pb+Pb interactions.

Acknowledgments

The author would like to express her sincerest gratitude and warm thanks to Wit Busza for everything she has learned from him over the years of cooperative work on the PHOBOS experiment. Thanks and congratulations are due to the workshop organizers for putting together a lively, interesting and very successful meeting.

This work was in part supported by the National Science Centre grants DEC-2011/03/B/ST2/0261 and DEC-2013/08/M/ST2/00320.

References

- [1] J.-Y. Ollitrault, *Anisotropy as a signature of transverse collective flow*, Phys. Rev. D **46** (1992) 229.
- [2] A. M. Poskanzer and S. A. Voloshin, *Methods for analyzing anisotropic flow in relativistic nuclear collisions*, Phys. Rev. **C58** (1998) 1671–1678, [arXiv:nuc1-ex/9805001](#).
- [3] PHENIX Collaboration, K. Adcox et al., *Flow Measurements via Two-Particle Azimuthal Correlations in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV*, Phys. Rev. Lett. **89** (2002) 212301.
- [4] N. Borghini, P. M. Dinh, and J. Y. Ollitrault, *New method for measuring azimuthal distributions in nucleus-nucleus collisions*, Phys. Rev. **C63** (2001) 054906.
- [5] N. Borghini, P. M. Dinh, and J. Y. Ollitrault, *Flow analysis from multiparticle azimuthal correlations*, Phys. Rev. **C64** (2001) 054901.
- [6] N. Borghini, P. M. Dinh, and J. Y. Ollitrault, *Flow analysis from cumulants: a practical guide*, [arXiv:0110016 \[nuc1-ex\]](#).
- [7] A. Bilandzic, R. Snellings, and S. A. Voloshin, *Flow analysis with cumulants: direct calculations*, Phys. Rev. **C83** (2011) 044913, [arXiv:1010.0233 \[nuc1-ex\]](#).
- [8] S. A. Voloshin, A. M. Poskanzer, and R. Snellings, *Collective phenomena in non-central nuclear collisions*, [arXiv:0809.2949 \[nuc1-ex\]](#).
- [9] P. Sorensen, *Elliptic Flow: A Study of Space-Momentum Correlations In Relativistic Nuclear Collisions*, [arXiv:0905.0174 \[nuc1-ex\]](#).
- [10] BRAHMS Collaboration, I. Arsene et al., *Quark gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment*, Nucl. Phys. **A757** (2005) 1–27, [arXiv:nuc1-ex/0410020](#).
- [11] PHOBOS Collaboration, B. B. Back et al., *The PHOBOS perspective on discoveries at RHIC*, Nucl. Phys. **A757** (2005) 28–101, [arXiv:nuc1-ex/0410022](#).
- [12] PHENIX Collaboration, K. Adcox et al., *Formation of dense partonic matter in relativistic nucleus nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration*, Nucl. Phys. **A757** (2005) 184–283, [arXiv:nuc1-ex/0410003](#).
- [13] STAR Collaboration, J. Adams et al., *Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR collaboration's critical assessment of the evidence from RHIC collisions*, Nucl. Phys. **A757** (2005) 102–183, [arXiv:nuc1-ex/0501009](#).
- [14] ALICE Collaboration, K. Aamodt et al., *Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Rev. Lett. **105** (2010) 252302, [arXiv:1011.3914 \[nuc1-ex\]](#).
- [15] ALICE Collaboration, K. Aamodt et al., *Higher Harmonic Anisotropic Flow Measurements of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Rev. Lett. **107** (2011) 032301.
- [16] ALICE Collaboration, B. Abelev et al., *Anisotropic flow of charged hadrons, pions and (anti-)protons measured at high transverse momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Lett. **B 719** (2013) 18, [arXiv:1205.5761 \[nuc1-ex\]](#).

- [17] ALICE Collaboration, B. Abelev et al., *Harmonic decomposition of two-particle angular correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Lett. **B 708** (2012) 249, [arXiv:1109.2501 \[nucl-ex\]](#).
- [18] ATLAS Collaboration, *Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector*, Phys. Lett. **B707** (2012) 330.
- [19] ATLAS Collaboration, *Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector*, Phys. Rev. **C86** (2012) 014907, [arXiv:1203.3087 \[hep-ex\]](#).
- [20] ATLAS Collaboration, *Measurement of the distributions of event-by-event flow harmonics in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC*, [arXiv:1305.2942 \[hep-ex\]](#).
- [21] CMS Collaboration, *Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Rev. **C 87** (2013) 014902, [arXiv:1204.1409 \[nucl-ex\]](#).
- [22] CMS Collaboration, *Azimuthal anisotropy of charged particles at high transverse momenta in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Rev. Lett. **109** (2012) 022301, [arXiv:1204.1850 \[nucl-ex\]](#).
- [23] CMS Collaboration, *Measurement of the Azimuthal anisotropy of neutral pions in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Rev. Lett. **110** (2013) 042301, [arXiv:1208.2470 \[nucl-ex\]](#).
- [24] CMS Collaboration, *Measurement of higher-order harmonic azimuthal anisotropy in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, [arXiv:1310.8651 \[nucl-ex\]](#).
- [25] B. Alver and G. Roland, , Phys. Rev. C **81** (2010) 054905, [arXiv:1003.0194 \[nucl-ex\]](#).
- [26] P. Kovtun, D. T. Son, and A. O. Starinets, *Viscosity in strongly interacting quantum field theories from black hole physics*, Phys. Rev. Lett. **94** (2005) 111601, [hep-th/0405231](#).
- [27] ATLAS Collaboration, *Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector*, Phys. Rev. Lett. **110** (2013) 182302, [arXiv:1212.5198 \[hep-ex\]](#).
- [28] ATLAS Collaboration, *Measurement with the ATLAS detector of multi-particle azimuthal correlations in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, Phys. Lett. **B 725** (2013) 60, [arXiv:1303.2084 \[hep-ex\]](#).
- [29] CMS Collaboration, *Observation of long-range near-side angular correlations in proton-lead collisions at the LHC*, Phys. Lett. **B 718** (2013) 795, [arXiv:1210.5482 \[nucl-ex\]](#).
- [30] CMS Collaboration, *Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions*, Phys. Lett. **B 724** (2013) 213, [arXiv:1305.0609 \[nucl-ex\]](#).
- [31] ALICE Collaboration, *Long-range angular correlations on the near and away side in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, Phys. Lett. **B 719** (2013) 29, [arXiv:1212.2001 \[nucl-ex\]](#).
- [32] K. Dusling and R. Venugopalan, *Explanation of systematics of CMS p+Pb high multiplicity di-hadron data at $\sqrt{s_{NN}} = 5.02$ TeV*, Phys. Rev. **D 87** (2013) 054014, [arXiv:1211.3701 \[hep-ph\]](#).
- [33] K. Dusling and R. Venugopalan, *Comparison of the Color Glass Condensate to di-hadron correlations in proton-proton and proton-nucleus collisions*, Phys. Rev. **D 87** (2013) 094034, [arXiv:1302.7018 \[hep-ph\]](#).
- [34] Y. V. Kovchegov and D. E. Wertheim, *Long-Range Rapidity Correlations in Heavy-Light Ion Collisions*, [arXiv:1212.1195 \[hep-ph\]](#).
- [35] C. Y. Wong, *Momentum Kick Model Description of the Ridge in (Delta-phi)-(Delta eta) Correlation in pp Collisions at 7 TeV*, Phys. Rev. **C 84** (2011) 024901, [arXiv:1105.5871 \[hep-ph\]](#).
- [36] M. Strikman, *Momentum Kick Model Description of the Ridge in (Delta-phi)-(Delta eta) Correlation in pp Collisions at 7 TeV*, Acta Phys. Pol. **B 42** (2011) 2607.
- [37] S. Alderweireldt and P. Van Mechelen, *Obtaining the CMS Ridge effect with Multiparton Interactions*, [arXiv:1203.2084 \[hep-ph\]](#).
- [38] M. Ryskin, A. Martin, and V. Khoze, *Probes of multiparticle production at the LHC*, J. Phys. **G 38** (2011) 085006, [arXiv:1105.4987 \[hep-ph\]](#).
- [39] K. Werner, I. Karpenko, and T. Pierog, *The "Ridge" in Proton-Proton Scattering at 7 TeV*, Phys. Rev. Lett. **106** (2011) 122004, [arXiv:1011.0375 \[hep-ph\]](#).
- [40] T.-W. Deng, Z. Xu, and C. Greiner, *Elliptic and Triangular Flow and their Correlation in Ultrarelativistic High Multiplicity Proton Proton Collisions at 14 TeV*, Phys. Lett. **B 711** (2012) 301, [arXiv:1112.0470 \[hep-ph\]](#).
- [41] E. Avsar, Y. Hatta, C. Flensburg, J.-Y. Ollitrault, and T. Ueda, *Eccentricity and elliptic flow in pp collisions at the LHC*, J. Phys. **G 38** (2011) 124053, [arXiv:1106.4356 \[hep-ph\]](#).
- [42] P. Bozek, *Collective flow in p-Pb and d-Pb collisions at TeV energies*, Phys. Rev. **C 85** (2012) 014911, [arXiv:1112.0915 \[hep-ph\]](#).
- [43] P. Bozek and W. Broniowski, *Correlations from hydrodynamic flow in p-Pb collisions*, Phys. Lett. **B 718** (2013) 1557, [arXiv:1211.0845 \[hep-ph\]](#).
- [44] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.
- [45] M. Miller, K. Reygers, S. Sanders, and P. Steinberg, *Glauber modeling in high energy nuclear collisions*, Ann. Rev. Nucl. Part. Sci. **57** (2007) 205, [arXiv:0701025 \[nucl-ex\]](#).

- [46] ATLAS Collaboration, *Measurement of the centrality dependence of the charged particle pseudorapidity distribution in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector*, Phys. Lett. **B710** (2012) 363.
- [47] M. Gyulassy and X.-N. Wang, *HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions*, Comput. Phys. Commun. **83** (1994) 307, [arXiv:nuc1-th/9502021](#).
- [48] S. Agostinelli et al., *GEANT4 – a simulation toolkit*, Nucl. Instr. Meth. **A506** (2003) 250.
- [49] ATLAS Collaboration, *Measurement of the elliptic flow with multi-particle cumulants in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC*, ATLAS-CONF-2012-118 (2012).
- [50] C. Gale, S. Jeon, B. Schenke, P. Tribedy, and R. Venugopalan, *Event-by-event anisotropic flow in heavy-ion collisions from combined Yang-Mills and viscous fluid dynamics*, Phys. Rev. Lett. **110** (2013) 012302, [arXiv:1209.6330 \[nuc1-th\]](#).
- [51] C. Schen, U. Heinz, P. Huovinen, and H. Song, *Radial and elliptic flow in Pb+Pb collisions at the Large Hadron Collider from viscous hydrodynamic*, Phys. Rev. **C84** (2011) 044903, [arXiv:1105.3226 \[nuc1-th\]](#).
- [52] B. Schenke, P. Tribedy, and R. Venugopalan, *Fluctuating Glasma Initial Conditions and Flow in Heavy Ion Collisions*, Phys. Rev. Lett. **108** (2012) 252301, [arXiv:1202.6646 \[nuc1-th\]](#).
- [53] ATLAS Collaboration, *Measurement of reaction plane correlations in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, ATLAS-CONF-2012-049 (2012).
- [54] D. Teaney and L. Yan, *Nonlinearities in the harmonic spectrum of heavy ion collisions with ideal and viscous hydrodynamics*, Phys. Rev. **C86** (2012) 044908, [arXiv:1206.1905 \[nuc1-th\]](#).
- [55] J. Jia and D. Teaney, *Study on initial geometry fluctuations via participant plane correlations in heavy ion collisions: part II*, Eur. Phys. J. **C73** (2013) 2558, [arXiv:1205.3585 \[nuc1-ex\]](#).
- [56] H.-J. Drescher, A. Dumitru, A. Hayashigaki, and Y. Nara, *The eccentricity in heavy-ion collisions from color glass condensate initial conditions*, Phys. Rev. **C74** (2006) 044905, [arXiv:0605012 \[nuc1-th\]](#).
- [57] PHENIX Collaboration, A. Adare et al., *Dihadron azimuthal correlations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, Phys. Rev. **C78** (2008) 014901, [arXiv:0801.4545 \[nuc1-ex\]](#).