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Measurement of the azimuthal anisotropy of charged particles in 5.02 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions with the ATLAS experiment

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The high-statistics data collected by the ATLAS experiment during the 2015 Pb+Pb and 2017 Xe+Xe LHC runs are used to measure charged particle azimuthal anisotropy. The flow harmonics, v_n (n=2–7), are obtained with the two-particle correlation, scalar-product and event-plane methods. Measurements of differential and global flow harmonics in Pb+Pb and Xe+Xe collisions in a wide range of transverse momenta (p_{T} up to 60 GeV), pseudorapidity ($|\eta| < 2.5$) and collision centrality (0–80%) are presented. The higher order harmonics, sensitive to fluctuations in the initial state, are precisely measured. In this analysis the v_7 is obtained for the first time. The new flow results allow to improve the understanding of initial conditions of nuclear collisions, hydrodynamical behavior of the quark-gluon plasma and the parton energy loss.

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1. Introduction

ATLAS heavy-ion program delivered a rich set of results constraining the understanding of the quark-gluon plasma (QGP) produced in ultra-relativistic nuclear collisions. One of widely studied signatures of the QGP is the anisotropy observed in the charged particle production [1, 2]. The strongly-interacting QGP is found to be a nearly perfect liquid with very low viscosity, which exhibits the hydrodynamic flow. The anisotropy arises from the initial geometry of a collision, where the nuclear matter is highly compressed in an ellipsoidal volume. This spatial asymmetry is transferred via the pressure gradients, that develop inside the plasma, to the final anisotropy in the momentum space. As a result, particles produced in a collision are emitted in preferential azimuth directions. The final state particle distributions are commonly studied using the Fourier series: $\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Psi_n)]$, where ϕ is an azimuthal angle of charged particle, Ψ_n is a reaction plane angle and v_n is a Fourier coefficient of n-th order. The v_n are known as flow harmonics with the v_2 (*elliptic flow*) resulting from the elliptical initial asymmetry of the interaction region and the higher-order components reflecting fluctuations in the initial geometry of the interaction zone.

This report presents the recent measurements of v_n harmonics obtained by the ATLAS experiment in $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb [3] and $\sqrt{s_{NN}} = 5.44$ TeV Xe+Xe [4] collisions. The data sample used in Pb+Pb analysis corresponds to 0.49 nb^{-1}, while Xe+Xe measurement is based on 3 μb^{-1} integrated luminosity collected by the ATLAS detector [5] during heavy-ion LHC runs in 2015 and 2017, respectively. In both collision systems the v_n harmonics are calculated with the scalar-product (SP) [6], the event-plane (EP) [2] and the two-particle correlation (2PC) [2]. Due to high statistics of the Pb+Pb data, the Fourier coefficients are precisely measured over a wide range of kinematic variables (p_T up to 60 GeV, $|\eta| < 2.5$) and centrality (0–80%). The flow harmonics measurement provides valuable information about the initial state, its evolution and in particular about the hydrodynamic behavior of the QGP. Moreover, v_n measured at high p_T reflect the path-length dependence of the parton energy loss in QGP. The smaller size of Xe nucleus introduce larger event-by-event fluctuations in the initial geometry compared to Pb+Pb, but, at the same time, the QGP produced in the lighter system is expected to show larger viscous effects. Both effects are studied in Xe+Xe collisions.

2. v_n harmonics in Pb+Pb collisions

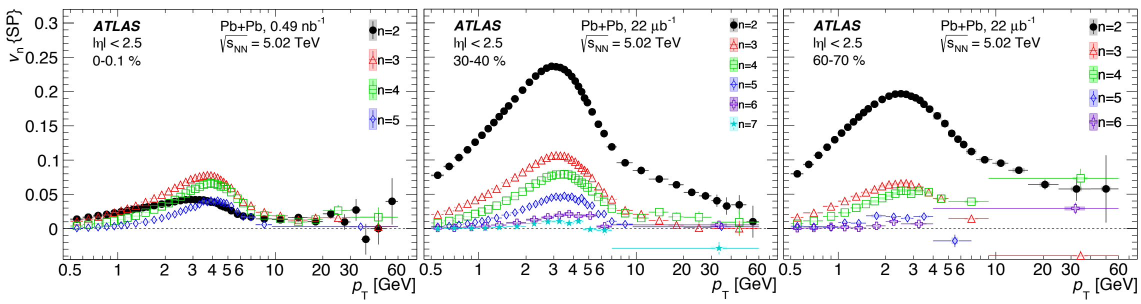

Figure 1: The $v_n(p_T)$ obtained with the SP method in: ultra-central (0-0.1%), mid-central (30-40%) and peripheral (60-70%) Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [3].

Using the large sample of Pb+Pb data, ATLAS measured the v_n harmonics in a wide range of centralities from ultra-central to peripheral collisions, and also in a broad p_T range up to 60 GeV [3].

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Figure 1 shows $v_n(p_T)$ integrated over $|\eta| < 2.5$ obtained with the SP method in three centrality intervals: 0–0.1% (ultra-central), 30–40% (mid-central) and 60–70% (peripheral). The largest anisotropies are observed in mid-central collisions. The flow harmonics show a characteristic p_T dependence: there is an almost linear rise up to $\sim$2 GeV, then a gradual increase to the maximum at p_T = 3–4 GeV and a steady fall for higher p_T. The v_2 is positive even at the highest p_T, providing the information about parton energy loss. The ordering of v_n harmonics ($v_n > v_{n+1}$) is reversed in ultra-central collisions, where higher order harmonics are larger than the elliptic flow ($v_3 > v_4 > v_5 \approx v_2$), indicating that the dominant source of observed flow comes from the initial fluctuations. Moreover, such large data sample allows for the first time for the measurement of v_7 harmonic, which is found to be non-zero for the mid-central events.

3. Comparison of different methods

Figure 2 presents the v_n harmonics measured with the SP method and with the complementary event-plane (EP) method. Results are shown as a function of centrality expressed by the number of nucleons participating in the Pb+Pb collision, $\langle N_{part}\rangle$, and are integrated over $0.5 < p_T < 60$ GeV and $|\eta| < 2.5$. The $v_2\{SP\}$ is found to be larger than $v_2\{EP\}$ for the most of collision centralities. The ratio $\frac{v_2\{SP\}}{v_2\{EP\}}$ reaches maximum (~ 1.03) for 20-50% centrality interval. A small difference between both methods is expected as the SP method measures $\sqrt{v_n^2}$, whereas the quantity measured with the EP method depends on the detector resolution and thus, lies between $\langle v_n\rangle$ and $\sqrt{v_n^2}$ [7]. For higher-order flow harmonics both methods give consistent values.

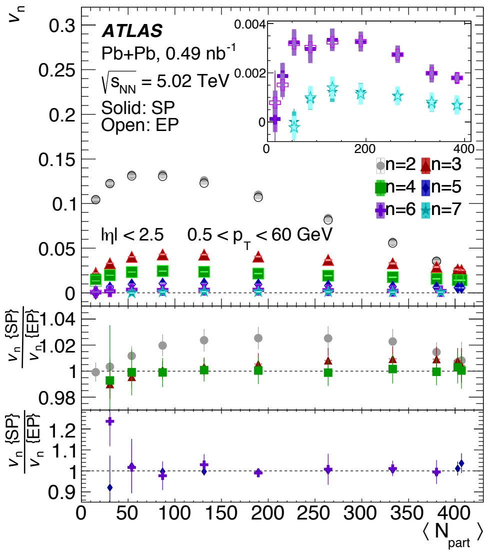

Figure 2: Comparison of the v_n obtained with the SP and EP methods as a function of $\langle N_{part}\rangle$, integrated over $0.5 < p_T <$ 60 GeV [3].

4. Universal scaling of v_n harmonics

The p_T dependence of flow harmonics exhibits two features. Firstly, there is a change in the v_n magnitude from one centrality to another. Secondly, the peak v_n is reached at different p_T from one centrality to another. ATLAS performed a scaling procedure [3], which yields universal shapes for the flow coefficients across different centrality classes. In the procedure, the x- and y-axes in each centrality class were scaled to best agree with the 0-60% centrality reference shape. The left panel in Figure 3 corresponds to the $v_2(p_T)$ harmonics obtained with 2PC method in several 5%-wide centrality classes. The corresponding scaled-v_2 is shown in the right panel in Figure 3. Such scaling indicates that the QGP systems evolving from different initial conditions may have similar properties. Similar scaling is observed for the v_3 harmonic.

5. Azimuthal anisotropy in Xe+Xe collisions

The 2017 LHC heavy-ion run provided the opportunity to study the azimuthal anisotropy in Xe+Xe collisions. Xe ions are almost twice smaller than Pb ions implying larger spatial fluctuations, which should result in increased flow signal. ATLAS measured the $v_n\{Xe+Xe\}$ harmonics

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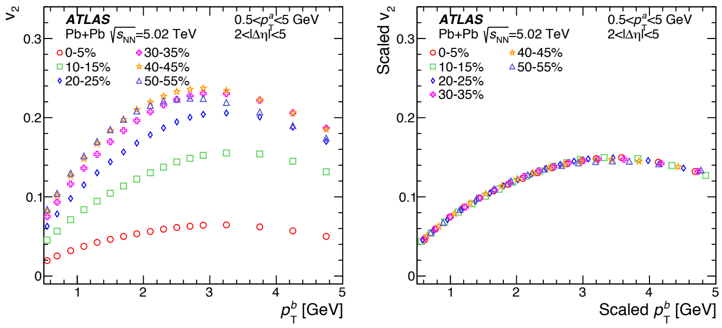

Figure 3: Left: the $v_2(p_T)$ obtained with the 2PC method for different centrality classes. Right: the corresponding scaled-$v_2(p_T)$ in the same centrality classes [3].

for $n = 2$–5 in wide ranges of p_T (up to 20 GeV for v_2), $|\eta| < 2.5$ and collision centrality [4]. The $v_n(p_T)$ obtained with SP method is shown in Figure 4 in three centrality intervals: 0–5%, 30–40% and 50–60%. The p_T dependence is similar to that observed in Pb+Pb collisions. The elliptic flow is dominant in most centrality intervals except for the most central collisions (0-5%), where v_3 values are larger than v_2 for $p_T > 3$ GeV.

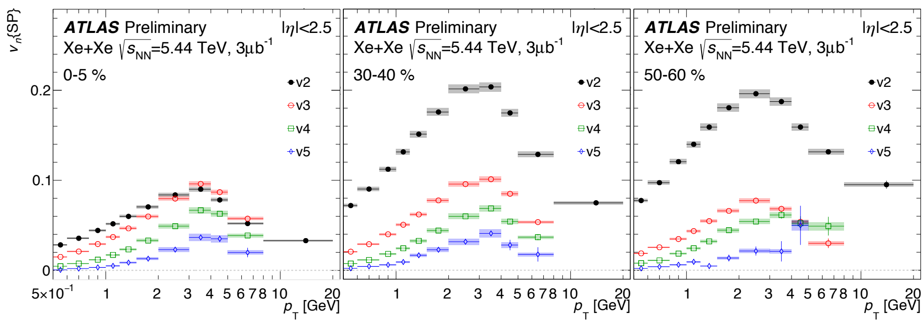

Figure 4: The $v_n(p_T)$ measured with the SP method in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV in three centrality intervals: 0–5%, 30–40% and 50–60% [4].

The quantitative comparisons of the v_2 and v_3 between the Pb+Pb and Xe+Xe systems are shown in the Figure 5. The v_n harmonics, integrated over p_T = 0.5-5 GeV, obtained with the 2PC method are presented as a function of centrality percentiles. The ratio of Xe+Xe v_n to Pb+Pb v_n, shown in the right panel, are quite consistent with the theoretical predictions from Ref. [8]. The Xe+Xe v_2 and v_3 values are significantly larger than for Pb+Pb collisions in the most central events. This behaviour is understood as resulting from the larger initial fluctuations present in the smaller system, which leads to flow enhancement in Xe+Xe collisions. The opposite effect is observed in mid-central and peripheral collisions where the Xe+Xe v_n values are observed to be smaller than those in Pb+Pb collisions. In these centrality intervals flow harmonics are expected to be reduced in Xe+Xe system due to its larger viscosity. Such behaviour is confirmed by theoretical predictions, also shown in Figure 5.

6. Summary

ATLAS performed a comprehensive study of azimuthal anisotropy of charged particles using $\sqrt{s_{NN}} = 5.02$ TeV Pb+Pb and $\sqrt{s_{NN}} = 5.44$ TeV Xe+Xe collisions. The flow harmonics were measured up to v_7 with high precision thanks to large statistics of experimental data. In ultra-central

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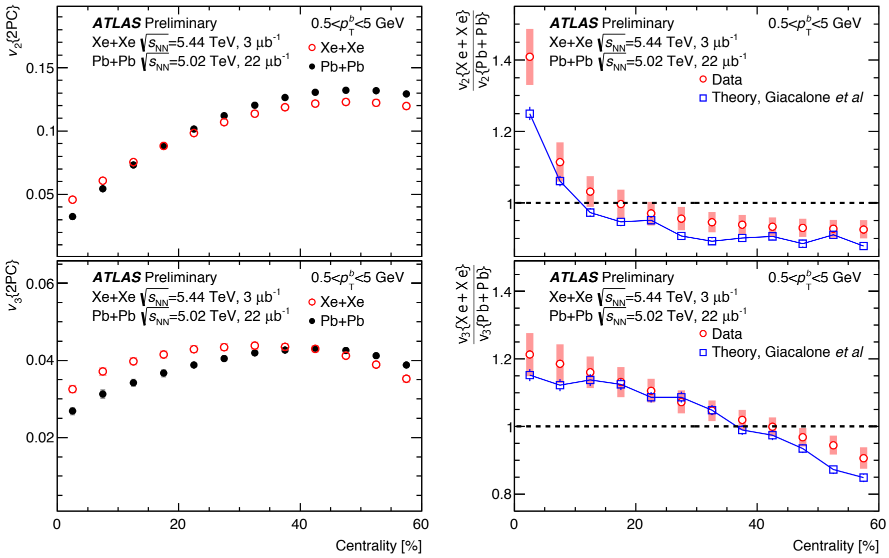

Figure 5: Left panels: the v_2 (top) and v_3 (bottom) harmonics as a function of collision centrality measured with the 2PC method in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV integrated over $0.5 < p_T < 5$ GeV. Right panels: Ratios of the $v_n\{Xe+Xe\}$ to the $v_n\{Pb+Pb\}$ for $n = 2$ (top) and $n = 3$ (bottom) [4], compared with theoretical predictions [8].

collisions Pb+Pb a reversed v_n ordering, $v_3 > v_4 > v_5 \approx v_2$, is observed, implying that in these collisions the azimuthal anisotropy arises from the initial state fluctuations. A scaling procedure was performed for Pb+Pb data, which showed an universal shape of $v_n(p_T)$ (n=2,3) across different centrality classes. Results obtained with Xe+Xe and Pb+Pb collisions were compared. In the most central events, due to larger fluctuations expected in the lighter system, the Xe+Xe v_2 and v_3 values are observed to be larger than those in Pb+Pb. This effect is compensated in more peripheral collisions, where viscous effects are expected to be more pronounced, and the flow measured in the Xe+Xe is smaller than in the Pb+Pb system.

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