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Recent results on collectivity and correlations in heavy-ion collisions from ATLAS

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The measurement of the multi-particle cumulants with 0.47 nb^{-1} of Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} =$ 5.02 TeV with the ATLAS detector at the LHC is presented. To investigate the impact of fluctuations arising from intrinsic centrality or volume fluctuations, the cumulants measured in two different event classes used for centrality definition are compared, one based on the total transverse energy deposited in the Forward Calorimeter and the second based on the number of charged particles reconstructed at midrapidity. In the most central collisions significant differences between two events classes are observed, and they are also present in the mid-central collisions but with smaller magnitude. Two new measurements of heavy-flavor flow are also presented. First, the production of muons from heavy-flavor decays is measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV using 0.14 nb^{-1} of data. Second, the elliptic flow of prompt and non-prompt J/ψ is measured in the di-muon decay channel in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an integrated luminosity of 0.42 nb^{-1}. Both measurements provide evidence for the presence of heavy-quark flow in heavy-ion collisions.

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1. Introduction

One of the most powerful tools to study the properties of the quark-gluon plasma (QGP) created in relativistic heavy-ion collisions is the azimuthal anisotropy of produced particles. Typically the azimuthal distribution of charged particles is characterized by the Fourier decomposition of $\mathrm{d}N/\mathrm{d}\phi \propto 1+2\Sigma_{n=1}^{\infty} v_n \cos\, n(\phi\ -\ \Phi_n)$, where v_n and Φ_n represent the magnitude and the event-plane angle of the n-th order flow harmonic. It is understood that in high energy A+A collisions v_n coefficients carry information about the hydrodynamic medium response to the asymmetric initial conditions [1].

A well-established and widely-used technique to measure the v_n harmonics relies on calculating cumulants ($c_n\{k\}$) from the multi-particle correlations [2]. This method allows the study of event-by-event correlations among the magnitudes of two different order flow harmonics v_n and v_m via the 4-particle symmetric cumulants ($sc_{n,m}\{4\}$) [3]. Similarly, the 3-particle asymmetric cumulant ($ac_n\{3\}$) is sensitive to correlations involving both the magnitude and phase of two flow harmonics v_n and v_{2n} [4]. Cumulants are often calculated for events with similar activity (event classes), defined using observables that are monotonically related to the particle multiplicity (such as charged particle tracks multiplicity, sum of transverse energy, etc.). Due to fluctuations in the particle production process, the centrality for events selected in different event classes can fluctuate from event-to-event. Recent measurements from the ATLAS experiment [5] show the impact of the centrality fluctuations on the cumulants, symmetric cumulants and asymmetric cumulants in the Pb+Pb collisions.

The azimuthal anisotropy of the heavy quarks can provide valuable information about the QGP transport properties. Heavy quarks are primarily produced at the early stage of the collision and acquire azimuthal anisotropy through the interactions with the collectively expanding medium [6]. This proceedings contribution reports new ATLAS measurements of heavy-flavor quarks flow via prompt and non-prompt J/ψ candidates and muons originating from semi-leptonic decays of heavy-quarks in Pb+Pb collisions.

2. Flow fluctuations in 5.02 TeV Pb+Pb collisions

The standard observable used in the ATLAS experiment to quantify centrality of the heavy-ion collision is the transverse energy deposited in Forward Calorimeter (ΣE_{T}). The left panel of Figure 1 shows the correlation between ΣE_{T} and the number charged particle tracks ($N_{\mathrm{ch}}^{\mathrm{rec}}$) reconstructed with the $p_{\mathrm{T}} > 0.5$ GeV and $|\eta| < 2.5$. The linear correlation between these two quantities indicate that they are both sensitive to the number of particles created in the collision. However events with the same ΣE_{T} could have significant fluctuations in $N_{\mathrm{ch}}^{\mathrm{rec}}$ and the other way around, events with fixed $N_{\mathrm{ch}}^{\mathrm{rec}}$ could have different values of ΣE_{T}. The mean and root-mean-square values of $N_{\mathrm{ch}}^{\mathrm{rec}}$ (ΣE_{T}) calculated in narrow bins of ΣE_{T} ($N_{\mathrm{ch}}^{\mathrm{rec}}$) are shown in the middle (left) panel of Figure 1. A linear relation between $\langle N_{\mathrm{ch}}^{\mathrm{rec}}\rangle$ and ΣE_{T} is observed over entire ΣE_{T} range. Same relation in seen when looking at the $\langle \Sigma E_{\mathrm{T}}\rangle$ in narrow bins of $N_{\mathrm{ch}}^{\mathrm{rec}}$ until the most central collisions where $\langle \Sigma E_{\mathrm{T}}\rangle$ deviates from the linear relation to $N_{\mathrm{ch}}^{\mathrm{rec}}$. This suggests that the true centrality distribution is more smeared for the events with the same $N_{\mathrm{ch}}^{\mathrm{rec}}$ than for events with the same ΣE_{T}, and a reference event class based on $N_{\mathrm{ch}}^{\mathrm{rec}}$ may have different centrality fluctuations than the event class based on

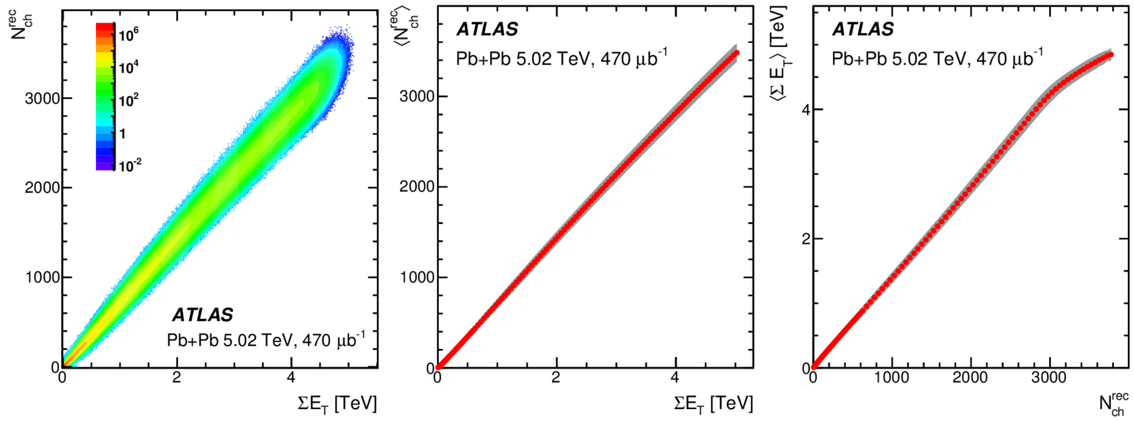

Figure 1: Correlation between $N_{\text{ch}}^{\text{rec}}$ and ΣE_{T} in the Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ (left). The mean values of $N_{\text{ch}}^{\text{rec}}$ calculated in narrow slices of ΣE_{T} (middle) and the mean values of ΣE_{T} calculated in narrow slices of $N_{\text{ch}}^{\text{rec}}$ (right). Shaded bands show root-mean-square of either $N_{\text{ch}}^{\text{rec}}$ or ΣE_{T} [7].

ΣE_{T}. The influence of centrality fluctuations on the measurement of flow harmonics is investigated by comparing cumulants calculated using ΣE_{T}-based reference event class and $N_{\text{ch}}^{\text{rec}}$-based event class.

Figure 2 shows the ratios of $v_n\{2\}$ obtained from 2-particle cumulants in two event classes. The contribution of non-flow correlation is reduced by the requirement of pseudorapidity gap of at least $|\Delta\eta| > 2$ between two particles. In order to properly calculate the ratio, $v_n\{2\}$ values obtained in the narrow bins of $N_{\text{ch}}^{\text{rec}}$ ($v_n\{2, N_{\text{ch}}^{\text{rec}}\}$) are mapped to the $\langle \Sigma E_{\text{T}} \rangle$ and similarly $v_n\{2\}$ values calculated in the narrow bins of ΣE_{T} ($v_n\{2, \Sigma E_{\text{T}}\}$) are mapped to the $\langle N_{\text{ch}}^{\text{rec}} \rangle$. The results are then plotted as a function of $\langle \Sigma E_{\text{T}} \rangle$ scaled by 4.1 TeV (top row) and as a function of $\langle N_{\text{ch}}^{\text{rec}} \rangle$ scaled by 2800 (bottom row). Values used for scaling indicate where ΣE_{T} and $N_{\text{ch}}^{\text{rec}}$ distributions start to decrease sharply ("knee" of the centrality distribution) and the underlying centrality fluctuations are expected to be stronger. Such a representation of the x-axis gives more natural comparison of the overlap region in Pb+Pb collisions and better comparison between the two event activity observables. The ratios shown as a function of $\langle \Sigma E_{\text{T}} \rangle$/(4.1 TeV) are consistent with unity for v_3 and v_4, but for the most central collisions v_2 shows a few percent deviation. This result suggests that events selected in narrow bins of $N_{\text{ch}}^{\text{rec}}$ have slightly higher v_2 than events selected in narrow bins of ΣE_{T} when both ensembles are matched to the same $\langle \Sigma E_{\text{T}} \rangle$. The ratios plotted as a function of $\langle N_{\text{ch}}^{\text{rec}} \rangle$/2800 shows even more deviations from unity that are also present in v_3 and v_4. This behaviour is consistent with the hypothesis that $N_{\text{ch}}^{\text{rec}}$ have poorer centrality resolution and contains more events from less central collisions where events have larger v_n.

Figure 3 shows the direct comparison of normalized 4-particle cumulants ($nc_n\{4\}$) obtained with the two reference event classes for particles in the range $1.5 < p_{\text{T}} < 5.0$ GeV. The advantage of multi-particle cumulants normalized by the average value of $c_n\{2\}$ is that the p_{T} dependence is canceled out and $nc_n\{k\}$ directly reflects probability density distribution of v_n harmonic ($p(v_n)$). The $nc_2\{4, \Sigma E_{\text{T}}\}$ and $nc_2\{4, N_{\text{ch}}^{\text{rec}}\}$ values are negative for the most of the ΣE_{T} range. In the most central collisions both cumulants change sign, reach positive maximum and then decrease to zero again. The normalized cumulants for v_3 harmonic are negative over the entire ΣE_{T} range and

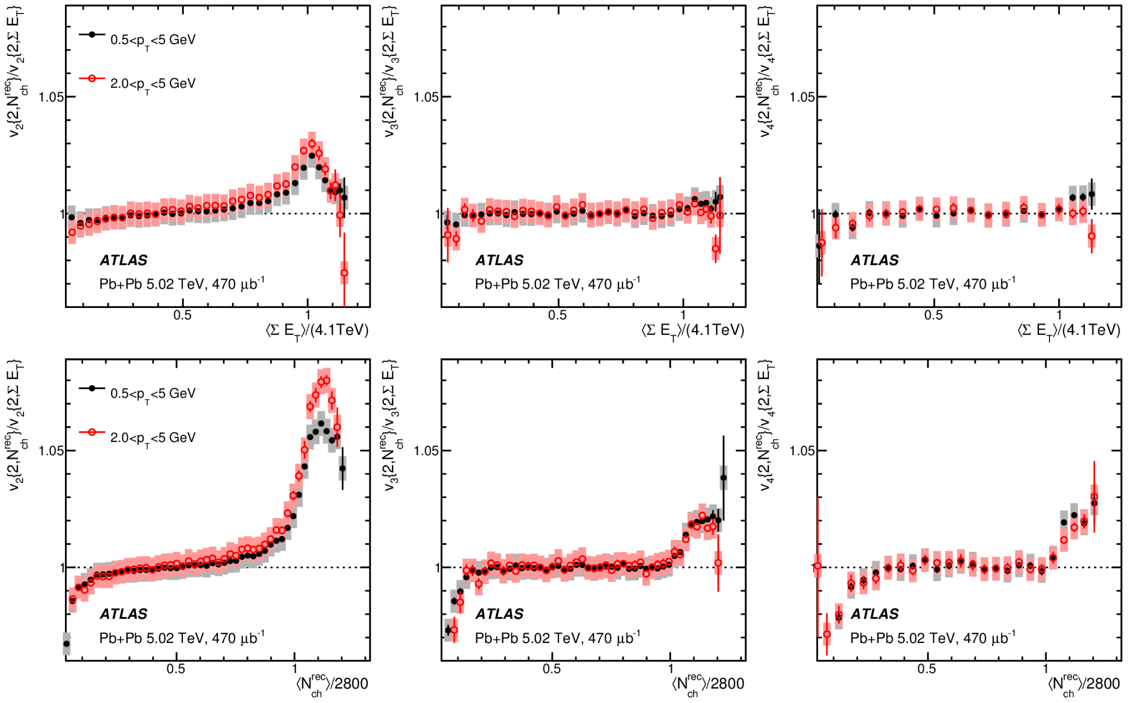

Figure 2: Ratio of flow harmonics measured in Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ using two event class definitions based on the $N_{\rm ch}^{\rm rec}$ and $\Sigma E_{\rm T}$ shown as a function of $\langle \Sigma E_{\rm T} \rangle$ (top) and $\langle N_{\rm ch}^{\rm rec} \rangle$ (bottom). Ratios are shown for the v_2 (left), v_3 (middle) and v_4 (right) harmonics. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively [7].

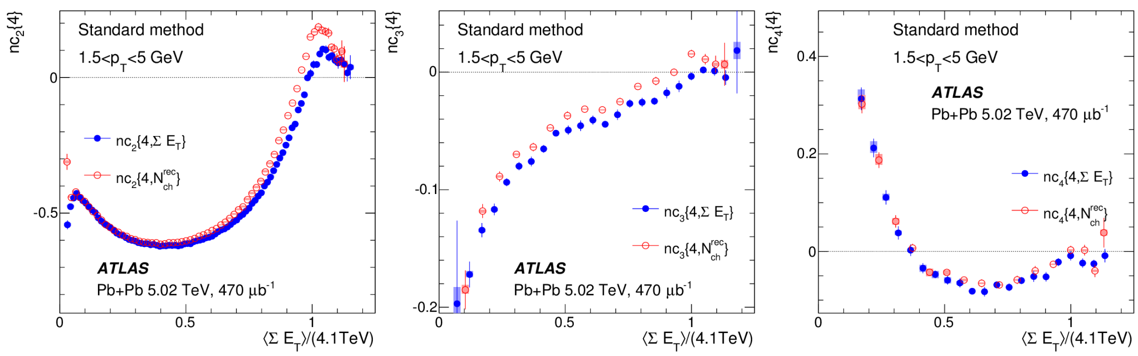

Figure 3: Comparison of $nc_2\{4\}$ (left), $nc_3\{4\}$ (middle) and $nc_4\{4\}$ (right) cumulants measured in Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ using two event class definitions and shown as a function of $\langle \Sigma E_{\rm T} \rangle$. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively [7].

approach zero in central collisions. The $nc_4\{4,\Sigma E_{\mathrm{T}}|N_{\mathrm{ch}}^{\mathrm{rec}}\}$ values change sign from positive in peripheral events to negative in the central events. Studies performed with the Glauber model [8] show that $c_n\{4\}$ is always negative when the reference event class is defined using the number of participating nucleons N_{part} or the collision impact parameter [9]. Positive values of $c_n\{4\}$ obtained when a reference class is based on multiplicity of final state particles (both $N_{\mathrm{ch}}^{\mathrm{rec}}$ and ΣE_{T}) could be explained by the non-Gaussian shape of $p(v_n)$ [10], but the impact of the centrality fluctuations is also seen in the higher values of the $nc_2\{4,N_{\mathrm{ch}}^{\mathrm{rec}}\}$. The normalized cumulants for v_2 and v_3 show significant differences between the two reference event classes, while the difference is much smaller for v_4. This suggests that the centrality fluctuations are potentially also important in mid-central collisions.

The impact of the centrality fluctuation on the normalized symmetric and asymmetric cumulants is also studied. Figure 4 shows that the $nsc_{2,3}\{4,N_{\mathrm{ch}}^{\mathrm{rec}}\}$ are significantly larger than the respective $nsc_{2,3}\{4,\Sigma E_{\mathrm{T}}\}$ over a broad centrality range, not only in most central collisions. In contrary to the normalized cumulants of single harmonics, where for each harmonic significant differences were observed for two reference classes, only $nsc_{2,3}\{4,N_{\mathrm{ch}}^{\mathrm{rec}}\}$ and $nsc_{2,3}\{4,\Sigma E_{\mathrm{T}}\}$ are significantly different. Other two cumulants, sensitive to the correlation between v_2 and v_4, are similar when calculated using the two reference event classes.

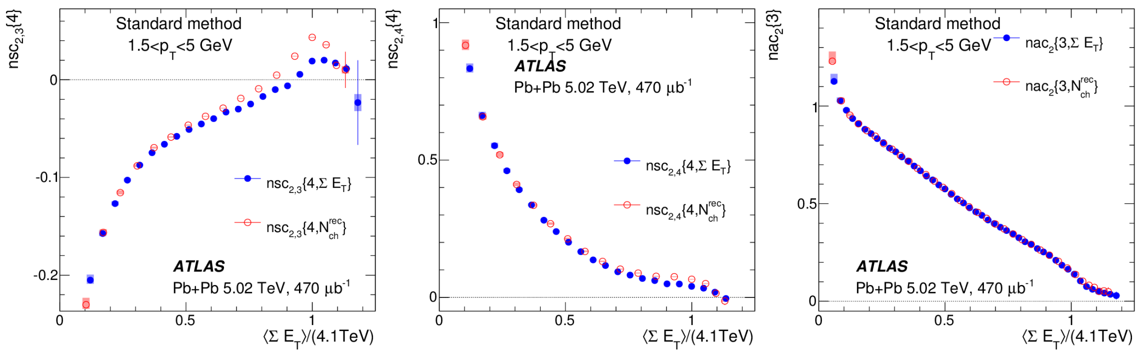

Figure 4: Comparison of $nsc_{2,3}\{4\}$ (left), $nsc_{2,4}\{4\}$ (middle) and $nac_2\{3\}$ (right) measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ using two event class definitions and shown as a function of $\langle \Sigma E_{\mathrm{T}} \rangle$. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively [7].

3. Heavy-flavor flow in 2.76 TeV and 5.02 TeV Pb+Pb collisions

In the early stages of the hadronic collision, charm (c) and bottom (b) quarks are produced via hard scatterings. As a result of their interactions with the collectively expanding medium, the heavy-quarks may acquire an azimuthal anisotropy. Measurements of the heavy-quark azimuthal anisotropy in Pb+Pb collisions at the LHC can provide valuable constraints on the QGP transport parameters [13].

Figure 5 shows v_2 and v_3 of heavy-flavor muons from semi-leptonic decays of heavy-quarks in five centrality intervals measured as a function of p_{T}. Heavy-flavor muons are distinguished from background muons using a “momentum-imbalance” variable that compares the momenta of the muons measured in the inner detector and muon spectrometer. Flow harmonics are measured

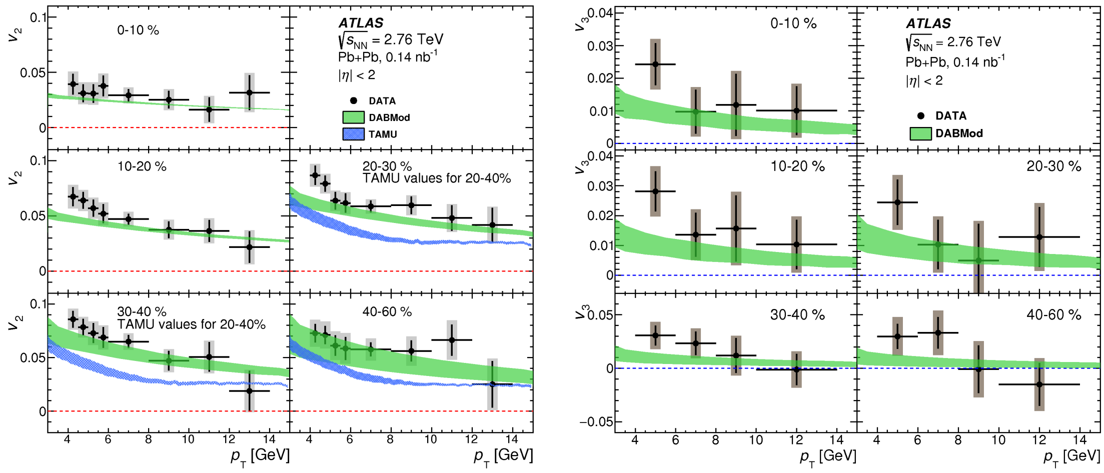

Figure 5: Comparison of the heavy-flavor muon v_2 (right) and v_3 (left) measured in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ with calculations from TAMU and DABMod models [11]. For the data, the error bars and shaded bands represent statistical and total uncertainties, respectively. For the model calculations bands represent theoretical systematic uncertainties.

by evaluating the yields differentially relative to the Φ_n plane, corrected for the jet bias caused by the back-to-back recoil jet that is usually associated to the signal muon. In all centrality classes, significantly non-zero v_2 is observed for muons in the range $4 < p_{\mathrm{T}} < 12$ GeV. The p_{T} dependence of v_2 for heavy-flavor muons is similar to those of charged hadrons v_2, with the characteristic drop at high p_{T}, but smaller in magnitude. The v_3 signal is smaller than the v_2 and shows a weaker variation over centrality. Experimental data are also compared to prediction from TAMU (transport of the heavy-flavor within the QGP) [14] and DABMod (energy-loss of heavy-flavor in the QGP) [15] models. DABMod gives better a description of v_2 than TAMU probably due to implementation of the event-by-event fluctuations into the model. For both v_2 and v_3 DABMod values are smaller than the measured values but become consistent at higher p_{T}.

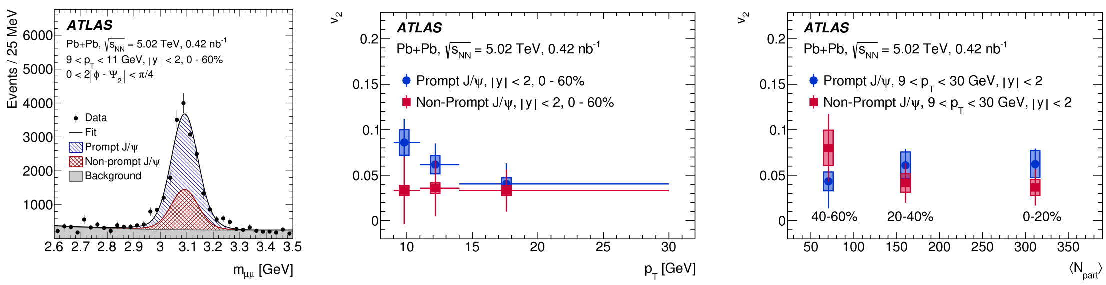

Figure 6: (left) Fit to the di-muon invariant mass for the signal extracted in azimuthal bin $0 < 2|\phi - \Psi_2| < \pi/4$. Prompt and non-prompt J/ψ v_2 as a function of centrality (middle) and p_{T} (right). The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively. The horizontal error bars in the middle plot represent the kinematic range of the measurement for each bin [12].

The elliptic flow of prompt (c-quarks) and non-prompt (product of b-quark decays) J/ψ is measured in the di-muon decay channel. The number of signal candidates and the fraction of signal that is non-prompt are extracted from the two-dimensional simultaneous fit of the invariant mass and pseudo-proper decay time of the di-muons from J/ψ candidates. An example plot with fit projection in one azimuthal bin is shown in the left panel of Figure 6. Centrality and p_{T} dependence of J/ψ v_2 is shown in Figure 6 for the candidates in the range between $9 < p_{\mathrm{T}} < 30$ GeV and $|\eta| < 2$ in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The data are consistent with non-zero elliptic flow over the entire studied kinematic range. Prompt J/ψ v_2 shows decreasing trend with p_{T} while for non-prompt J/ψ a constant non-zero value of v_2 is measured with a limited statistical significance. No significant centrality dependence is observed for prompt or non-prompt J/ψ for the results integrated over p_{T}.

4. Summary

This report presents recent ATLAS measurements of the flow harmonics in heavy-ion collisions at the LHC. The impact of the centrality fluctuations on multi-particle cumulants and symmetric cumulants is studied in the Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Results obtained using two reference event classes with different centrality resolution show significant differences in the most central Pb+Pb collisions, but a smaller effect is also observed in mid-central collisions. Two new measurements focused on the flow of heavy-quarks are also presented. The first focuses on the flow of the muons originating from semi-leptonic decays of heavy-quarks in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The second uses identified J/ψ candidates from Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Both measurements provide arguments confirming the flow of c- and b-hadrons created in heavy-ion collisions. These results provide new and comprehensive information about the nature of the flow of charged particles originating from light- and heavy-quarks.

References

[1] U. Heinz, R. Snellings, *Collective flow and viscosity in relativistic heavy-ion collisions*, Annu. Rev. Nucl. Part. Sci. **63** (2013) 123-151, arXiv:1301.2826[nucl-th]

[2] N.Borghini et al., *New method for measuring azimuthal distributions in nucleus-nucleus collisions*, Phys. Rev. C **63**, 054906, arXiv:0007063[nucl-th]

[3] A. Bilandzic et al., *Generic framework for anisotropic flow analyses with multi-particle azimuthal correlations*, Phys. Rev. C **89**, 064904 (2014), arXiv:1313.3572[nucl-th]

[4] ATLAS Collaboration, *Correlated long-range mixed-harmonic fluctuations measured in pp, p+Pb and low-multiplicity Pb+Pb collisions with the ATLAS detector*, Phys. Lett. B **789** (2019) 444, arXiv:1807.02012[nucl-ex]

[5] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003

[6] S. Cao, G.-Y. Qin, S. A. Bass, *Heavy-quark dynamics and hadronization in ultrarelativistic heavy-ion collisions: Collisional versus radiative energy loss*, Phys. Rev. C **88**, 044907, arXiv:1308.0617[nucl-ex]

[7] ATLAS Collaboration, *Fluctuations of anisotropic flow in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector*, arXiv:1904.04808[nucl-ex]

[8] M. L. Miller et al., *Glauber Modeling in High Energy Nuclear Collisions*, Ann. Rev. Nucl. Part. Sci. **57** (2007) 205-243, arXiv:nucl-ex/0701025

[9] B. Alver et al., *Importance of correlations and fluctuations on the initial source eccentricity in high-energy nucleus-nucleus collisions*, Phys. Rev. C **77** (2008) 014906, arXiv:0711.3724[nucl-ex]

[10] M. Zhou and J. Jia, *Centrality fluctuations in heavy-ion collisions*, Phys. Rev. C **98** (2018) 044903, arXiv:1803.01812[nucl-ex]

[11] ATLAS Collaboration, *Measurement of the suppression and azimuthal anisotropy of muons from heavy-flavor decays in Pb+Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV with the ATLAS detector*, Phys. Rev. C **98** (2018) 044905, arXiv:1805.05220[nucl-ex]

[12] ATLAS Collaboration, *Prompt and non-prompt J/ψ and $\psi(2s)$ suppression at high transverse momentum in 5.02 TeV Pb+Pb collisions with the ATLAS experiment*, Eur. Phys. J. C **78** (2018) 762, arXiv:1805.04077[nucl-ex]

[13] X. Dong, Y.-J. Lee, and R.Rapp, *Open Heavy-Flavor Production in Heavy-Ion Collisions*, Annu. Rev. Nucl. Part. Sci. **69** (2019) 417-45, arXiv:1401.3817[nucl-th]

[14] M. He, R. J. Fries, and R. Rapp, *Heavy Flavor at the Large Hadron Collider in a Strong Coupling Approach*, Phys. Lett. B **735** (2014) 445, arXiv:1903.07709[nucl-ex]

[15] C. A. G. Prado et al., *Event-by-event correlations between soft hadrons and D^0 mesons in 5.02 TeV PbPb collisions at the CERN Large Hadron Collider*, Phys. Rev. C **96** (2017) 064903, arXiv:1611.02965[nucl-th]