# Heavy ion physics at ATLAS and CMS: flow harmonics across systems ($pp$, $p$+Pb, Xe+Xe, Pb+Pb)

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The collective flow of produced particles is one of the signatures of the creation of the Quark-Gluon Plasma (QGP) in heavy ion collisions. However, similar long-range azimuthal correlations are observed at the LHC energies also in proton-lead and even proton-proton collisions. Extensive and detailed studies of flow harmonics are performed by the ATLAS and the CMS experiments in order to understand mechanisms responsible for these correlations.

Long-range azimuthal correlations of particles produced in heavy ion collisions at high energies can be explained as a consequence of the asymmetry of the overlap area of colliding nuclei leading to differences in the pressure gradients in QGP which affect the particle production. The distribution of azimuthal angles, $\phi$, of charged particles with respect to the event plane features a cosine-like modulation[1], which in the case of single events can be described by a complete Fourier series:

$$\frac{\mathrm{dN}}{\mathrm{d}\eta} \sim 1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \Phi_n)\right], \tag{1}$$

where $\Phi_n$ is the event plane angle and $v_n$ parameters are called flow harmonics. These harmonics can be calculated not only using the Event Plane method, based on Eq. 1, but also from two- or multi-particle correlations, for example using the Scalar Product method, the standard cumulants method or the subevent cumulants method.

The importance of proper removal of non-flow effects in the calculations of flow harmonics, especially in $pp$ collisions, is evident in the studies of cumulants[2]. In the absence of non-flow effects the four-particle cumulants

$$c_n\{4\} = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle\rangle - 2\,\langle\langle e^{in(\phi_1-\phi_2)}\rangle\rangle^2 \tag{2}$$

should be negative as $c_n\{4\}_{\mathrm{flow}} = -v_n^4$. In Fig. 1 the standard cumulants calculated using all quadruplets of particles are positive and only in the three-subevent method, where particles compared are from different $\eta$ regions, $c_n\{4\}$ is negative in a wide multiplicity interval[2]. Obviously, the standard cumulants are sensitive to correlations between particles from jets.

The elliptic flow, $v_2$, is expected to reflect the geometry of collisions. In Fig. 2 the values of $v_2$ for $pp$, $p$+Pb and low-multiplicity Pb+Pb collisions[3] are shown as a function of multiplicity, $N_{\mathrm{ch}}$. For $pp$ collisions $v_2$ is constant, it increases with $N_{\mathrm{ch}}$ for two other systems and is the largest in Pb+Pb collisions, in which the overlap of these nuclei has the most elongated shape.

The subtle differences in the geometry are visible even in the comparison of harmonics for Xe+Xe and Pb+Pb collisions[4,5], as indicated by the ratios of harmonics shown in Fig. 3. Fluctuations of the shape of the overlap of nuclei are larger for Xe+Xe than for Pb+Pb collisions.

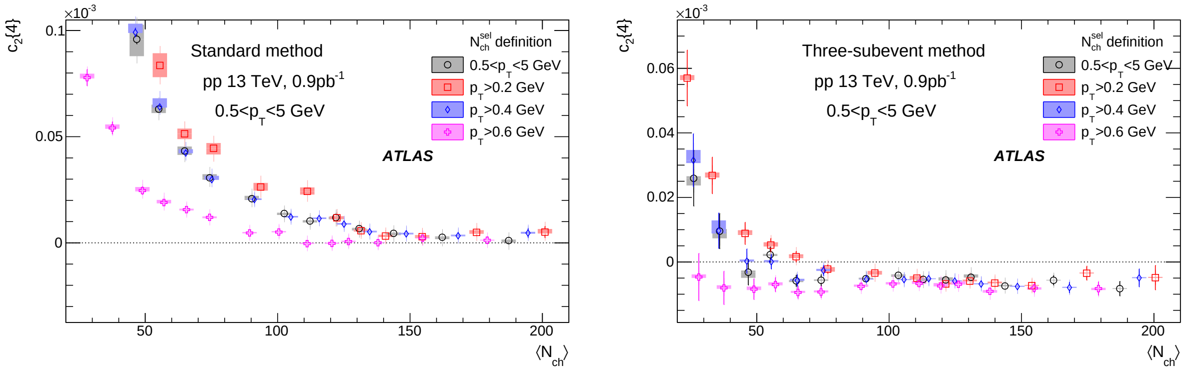


Figure 1 – The cumulant $c_2\{4\}$ values calculated for charged particles with $0.5 < p_{\mathrm{T}} < 5$ GeV with (left) the standard cumulant method and (right) the three-subevent cumulant method using the 13 TeV $pp$ data[2].

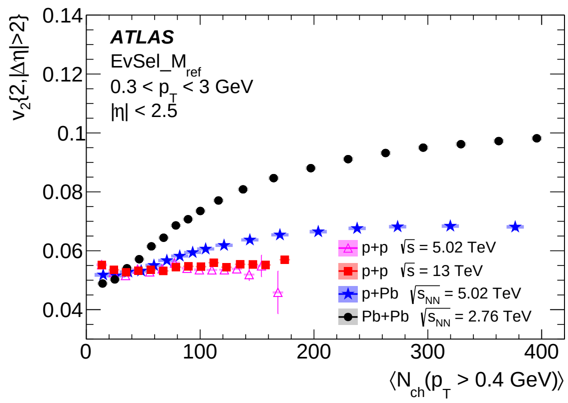


Figure 2 – Comparison of $v_2\{2, |\Delta\eta| > 2\}$, calculated for reference particles with $0.3 < p_{\mathrm{T}} < 3$ GeV, shown as a function of $\langle N_{\mathrm{ch}}(p_{\mathrm{T}} > 0.4\mathrm{GeV})\rangle$ for $pp$ collisions at $\sqrt{s}=$ 5.02 and 13 TeV, $p$+Pb collisions at $\sqrt{s_{NN}}=$ 5.02 TeV and low-multiplicity Pb+Pb collisions at $\sqrt{s_{NN}}=$ 2.76 TeV[3].

This causes that in the most central collisions $v_2$ and $v_3$ are larger in the first system. Contrary, in peripheral Xe+Xe collisions all harmonics are smaller than in Pb+Pb collisions as in this case fluctuations usually lead to smaller initial eccentricity.

In $p$+Pb collisions, an asymmetry in particle production in proton-going and lead-going direction is observed. This could influence also the ratio of flow harmonics at the same absolute pseudorapidity[6], shown in Fig. 4. All standard methods of elliptic flow calculations give smaller values in $p$-going than in Pb-going direction. However, they do not account for decorrelations (flow fluctuations along $\eta$), and once appropriate corrections are applied in calculations of $v_2\{\mathrm{SP}; \eta_{\mathrm{C}} = \eta_{\mathrm{ROI}}\}$ the differences between $p$-going and Pb-going sides largely disappear[6]. Detailed studies of flow decorrelations in Pb+Pb collisions[7] show that flow magnitude and event

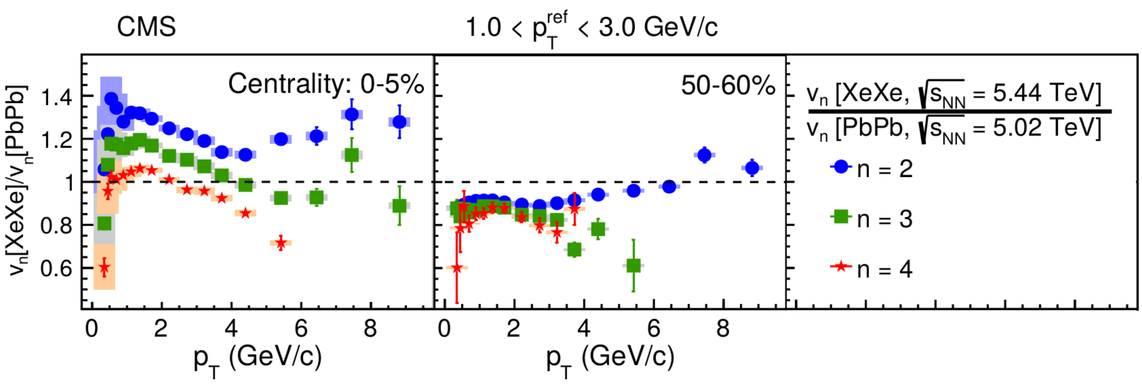


Figure 3 – Ratios of the $v_2$, $v_3$, and $v_4$ harmonic coefficients from two-particle correlations in Xe+Xe and Pb+Pb collisions as functions of $p_{\mathrm{T}}$ in two example centrality intervals[4].

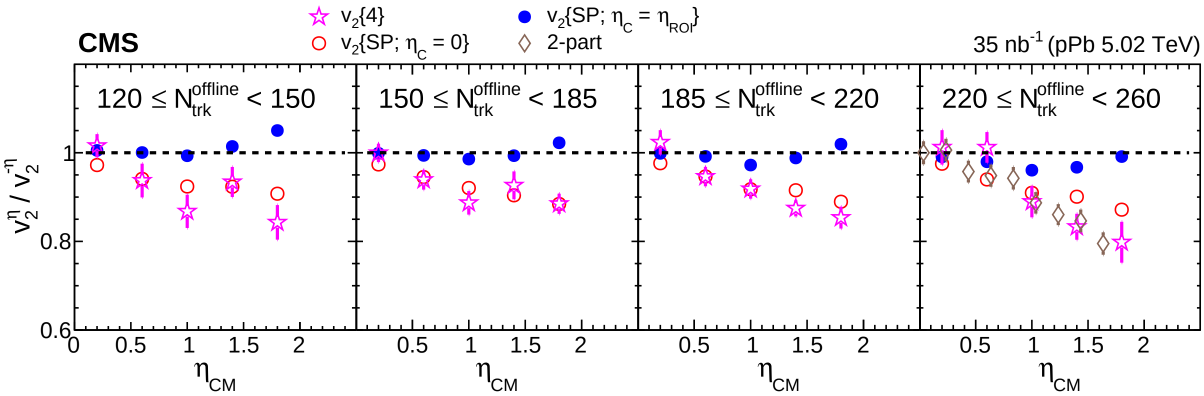


Figure 4 – Ratio of the $p$- to Pb-going side $v_2$ coefficients at comparable $\eta_{CM}$ values for $p$+Pb collisions[6].

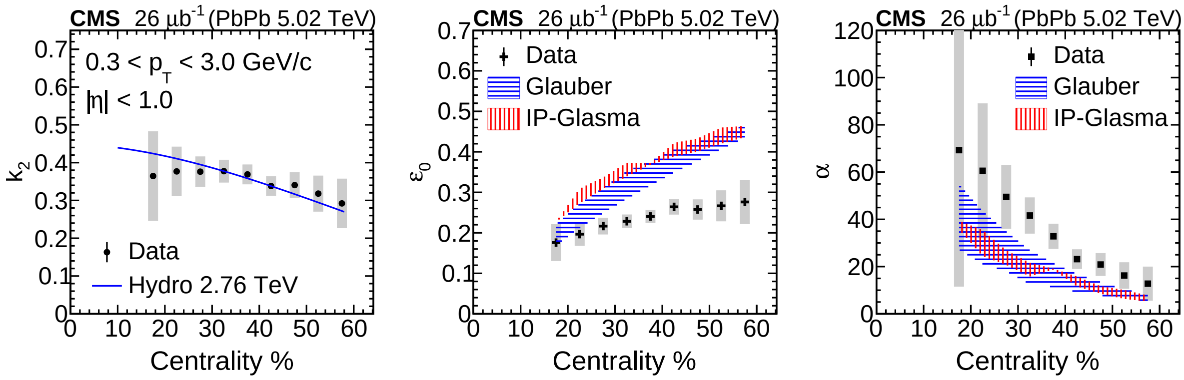


Figure 5 – Centrality dependence of the parameters extracted from elliptic power function fits to the unfolded $p(v_2)$ distributions[8].

plane rotation (twist) fluctuations are of similar order and increase approximately linearly with pseudorapidity.

Deeper insight into the properties of the initial eccentricity, $\varepsilon_n$, is possible in the studies of event-by-event flow fluctuations by measuring the probability function $p(v_n)$. Under some model assumptions, including emission of particles from $N$ sources and a linear response of $v_n$ to the initial eccentricity: $v_n = k_n \varepsilon_n$, $p(v_n)$ can be described by the elliptic power function[8], parameters of which are shown in Fig. 5. Lower values of parameter $\varepsilon_0$ than predicted by theoretical models may indicate that the assumption of linear response is not valid.

The flow fluctuations are sensitive to the number of sources of particles, $N_s$. It is thus possible to estimate $N_s$ using the ratio of $v_2\{2\}$ from two-particle correlations to $v_2\{4\}$ obtained from cumulants[2], as shown in Fig. 6. Results for $pp$ and $p$+Pb collisions are compatible and $N_s$ increases with mean multiplicity.

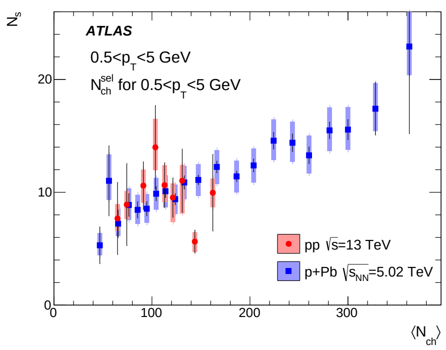


Figure 6 – The number of sources: $N_s = 4(v_2\{2\}/v_2\{4\})^4 - 3$, inferred from $v_2\{2\}$ and $v_2\{4\}$ measurements via the model framework in 13 TeV $pp$ and 5.02 TeV $p$+Pb collisions[2], for charged particles with $0.5 < p_T < 5$ GeV.

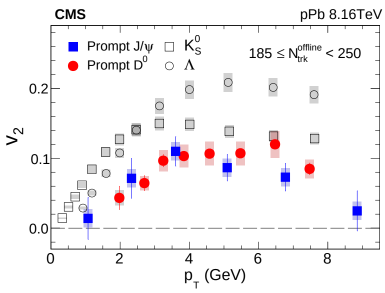


Figure 7 – Comparison of the $v_2$ results of the prompt $J/\psi$ mesons, as a function of $p_T$ for $p$+Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with those for for $K_0^S$, $\Lambda$ hadrons and $D^0$ mesons[9].

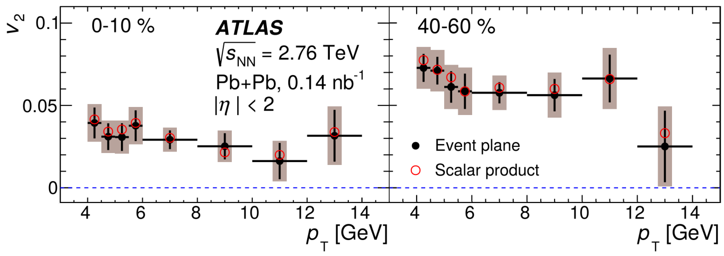


Figure 8 – The $p_T$ dependence of the Pb+Pb heavy-flavor muon $v_2$ for two centralities obtained from the Event Plane and the Scalar Product methods[10].

Flow harmonics are measured also for specific classes of particles. In Fig. 7 values of elliptic flow are shown for particles containing strange or charm quarks found in $p$+Pb collisions[9]. While $v_2$ as a function of $p_T$ has similar shape for both quark flavours, lower $v_2$ values indicate weaker collective behaviour of particles containing heavy quarks. The same conclusion can be drawn from the measurements of the flow of muons from heavy-flavour decays[10] shown in Fig. 8.

The results presented here on flow harmonics from ATLAS and CMS are not complete. There are several other studies, most recent of which include measurements of elliptic flow in $Z$ boson-tagged events[11], elliptic flow of high-$p_T$ particles[12] and mixed flow harmonics[13].

In summary, long range azimuthal correlations are present in all types of collisions available at the LHC and studied using ATLAS[14] and CMS[15] detectors. The flow harmonics magnitude depends on the type of collision, but similar general properties are observed in $p$+Pb, Xe+Xe and Pb+Pb collisions, while larger differences are found for $pp$ collisions. In the recent studies many different methods are use to remove contributions from non-flow effects. Their results allow better understanding of flow properties and relations to the initial conditions. Analyses of harmonics for different types of particles or specific classes of events provide additional information which can be used to test theoretical models.

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## References

1. ATLAS Collaboration, Phys. Lett. B **707** (2029) 330.
2. ATLAS Collaboration, Phys. Rev. C **97** (2018) 024904.
3. ATLAS Collaboration, Eur. Phys. J. C **77** (2017) 428.
4. CMS Collaboration, arXiv:1901.07997 [hep-ex].
5. ATLAS Collaboration, ATLAS-CONF-2018-011.
6. CMS Collaboration, Phys. Rev. C **98** (2018) 044902.
7. ATLAS Collaboration, Eur. Phys. J. C **76** (2018) 142.
8. CMS Collaboration, Phys. Lett. B **789** (2019) 643.
9. CMS Collaboration, Phys. Rev. Lett. **121** (2018) 082301.
10. ATLAS Collaboration, Phys. Rev. C **98** (2018) 044905.
11. ATLAS Collaboration, ATLAS-CONF-2017-068.
12. CMS Collaboration, Phys. Lett. B **776** (2017) 195.
13. ATLAS Collaboration, Phys. Lett. B **789** (2019) 444.
14. ATLAS Collaboration, JINST **3** (2008) S08003.
15. CMS Collaboration, JINST **3** (2008) S08004.