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Measurement of angular correlations in proton-proton and proton-lead collisions with the ATLAS detector at the LHC

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Piotr Janus* **on behalf of the ATLAS Collaboration**
AGH University of Science and Technology, Kraków, Poland
E-mail: piotr.janus@cern.ch

ATLAS measurements of angular correlations between particle pairs at large pseudorapidity separation in *pp* and *p*+Pb collisions are presented. The data were collected using a combination of the minimum-bias and high track-multiplicity triggers. A detailed study of the dependence of two-particle correlations on the charged particle multiplicity, transverse momentum of the pair constituents is shown. Measurements of multi-particle cumulants in the azimuthal angles of produced particles in wide pseudorapidity ($|\eta| < 2.5$) and multiplicity ranges, with the aim to extract a single particle anisotropy coefficient, v_2-v_4, are also presented. These measurements can help to understand the origin of the long-range correlations seen in high-multiplicity *pp* and *p*+Pb collisions.

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*Speaker.

1. Introduction

The fundamental feature of heavy-ion collisions is a production of a deconfined Quark Gluon Plasma (QGP). Hydrodynamic expansion of QGP is reflected in an enhancement in the azimuthal correlation of the particles production which extends over a broad pseudorapidity range. They are understood to be the result of azimuthal anisotropies of the single-particle distributions:

$$\frac{dN}{d\phi} = N_0\big(1+2\sum_{n=1}^{\infty} v_n \cos\left(n(\phi-\Phi_n)\right)\big), \tag{1.1}$$

where ϕ is the azimuthal angle of the particle emission, and the harmonics v_n and phase Φ_n are the magnitude and phase of the n-order anisotropy. These anisotropies are a consequence of spatial asymmetry in the interacting off-centre ions and fluctuations of collision geometry. Previously reported results provide evidence that produced matter behaves like a nearly perfect fluid [1–3]. However, the ridge which extends over large pseudorapidity range is also observed in p+Pb collisions [5, 6]. Possibly this structure originates from the same mechanism which is present in heavy ion collisions. However, alternative interpretation base on the saturation of parton distribution in the lead nucleus is capable to reproduce an observed effect in the p+Pb data [7–9].

Recent results show that the ridge structure in two-particle azimuthal correlations can be also observed in high-multilpicity pp collisions [10–13]. It is remarkable observation as formation of an extended nuclear matter was not expected in small collision systems. Similarly to p+Pb collisions the origin of the ridge could be different from that in Pb+Pb collisions. However, the recent study show it might comes from sinusoidal modulation of the per-event single particle azimuthal angle distributions [11].

2. Two particle correlations

The two particle correlations are measured as a function of the relative azimuthal angle $\Delta\phi \equiv \phi^a - \phi^b$ and relative pseudorapidity $\Delta\eta \equiv \eta^a - \eta^b$. The superscripts a and b denote the two particles in the pair, which are conventionally called "reference/trigger" and "associated" particles, respectively. The correlation function is defined as:

$$C(\Delta\phi,\Delta\eta) = \frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)}, \tag{2.1}$$

where $S(\Delta\phi,\Delta\eta)$ is a distribution constructed from same event and $B(\Delta\phi,\Delta\eta)$ is constructed from mixed events. All particles in the given event are used to obtain the S distribution. In result, it contains the physical correlations between particle pairs and correlations resulting from the acceptance effects. The mixed events are selected to have similar track multiplicity N_{ch}^{rec} and v_z coordinate of vertex such that acceptance effects are compensated in the S/B ratio. In order to take into account tracking efficiency varying with p_{T} and η, charged tracks are weighted by $1/\varepsilon(p_{\mathrm{T}},\eta)$ when calculating the pair distributions. Conventionally $C(\Delta\phi,\Delta\eta)$ function is normalized such that the $\Delta\phi$-averaged value is unity for $|\Delta\eta| > 2$. Then, by integrating the numerator and denominator of Eq. 2.1 over $|\Delta\eta|$ one can obtain one-dimensional correlation function $C(\Delta\phi)$:

$$C(\Delta\phi) = \frac{\int_2^5 d|\Delta\eta| S(\Delta\phi,\Delta\eta)}{\int_2^5 d|\Delta\eta| B(\Delta\phi,\Delta\eta)} = \frac{S(\Delta\phi)}{B(\Delta\phi)}. \tag{2.2}$$

The range $2 < |\Delta\eta| < 5$ is chosen to suppress contributions from the short range correlations (e.g. jets, resonance decays). A more physical meaning has "per-trigger-particle yield" which is $C(\Delta\phi)$ function with additional normalization:

$$Y(\Delta\phi) = \frac{\int_{-\pi/2}^{3\pi/2} B(\Delta\phi) d\Delta\phi}{N^a \int_{-\pi/2}^{3\pi/2} d\Delta\phi} C(\Delta\phi), \tag{2.3}$$

where N^a denotes the total number of trigger particles. This normalization allows subtraction of the $Y(\Delta\phi)$ distribution in one event-activity class from the $Y(\Delta\phi)$ distribution in another.

The template fitting method developed by ATLAS [11] is used to estimate and remove the impact of back to back dijets and other processes which correlates only a subset of the all particles in the event. This approach is assuming that jet-correlation has shape independent of the event multiplicity and at low multiplicity the structure of two particle correlation result predominantly from back to back dijets. With these assumptions the measured $Y(\Delta\phi)$ distribution is described by a superposition of a "peripheral" $Y(\Delta\phi)$ distribution, $Y^{periph}(\Delta\phi)$, scaled up by a multiplicative factor and a function describing ridge:

$$Y^{templ}(\Delta\phi) = G\big(1 + \sum_{n=2}^{\infty} 2v_{n,n} \cos(n\Delta\phi)\big) + FY^{periph}(\Delta\phi), \tag{2.4}$$

where F and $v_{n,n}$ are free parameters. The parameter G is fixed by the requirement that the integral of $Y^{templ}(\Delta\phi)$ is equal to the integral of measured $Y(\Delta\phi)$.

The summary of results in the inclusive p_T interval $0.5 < p_T < 5$ GeV is presented in Figure 1. It shows v_2, v_3 and v_4 obtained from the 5.02 TeV, 13 TeV pp and 5.02 TeV p+Pb template fits as a function of N_{ch}^{rec} (top panel) and as a function of a trigger particle p_T^a for th e$N_{ch}^{rec} \geq 60$ multiplicity range (bottom panel). Harmonics v_3 and v_4 are not shown for the 5.02 TeV pp data due to large systematic uncertainties associated with the choice of peripheral reference. From this results several conclusions can be drawn. In the p+Pb collisions v_2 increase with increasing N_{ch}^{rec} while in the pp collisions v_2 is independent of N_{ch}^{rec} within uncertainties. The pp and p+Pb $v_2(p_T)$ presents similar trends with both increasing with p_T at low p_T values, reaching a maximum near 3 GeV. Comparison of the v_2 between 13 and 5.02 TeV pp collisions show no significant energy dependence. More comprehensive summary can be found in Ref. [14].

3. Muon and charged particle correlations

As it was shown in the previous section particle production in high energy p+Pb and pp collisions display an enhancement in the azimuthal correlation of the particles production which extends over a broad pseudorapidity range. To further investigate phenomena observed in the p+Pb collisions the long-range correlation between muons and inclusive charged particles was measured by ATLAS [17]. Most of the prompt muons in the range $4 < p_T < 8$ GeV result from decay of heavy-flavor hadrons containing charm and bottom quark [15]. If a QGP is produced in p+Pb collisions, then partial thermalization of heavy-flavour may be visible in this momentum range [16]. Measuring this long-range correlation can provide information on the origin of the azimuthal anisotropy seen in p+Pb collisions.

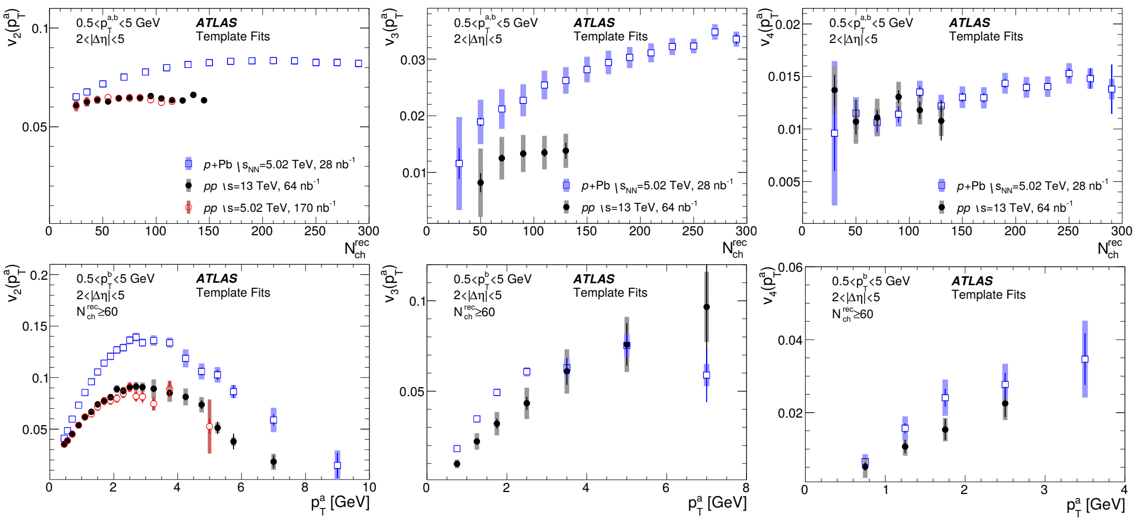

Figure 1: Comparison of the v_n obtained from the two-particle correlation method in 5.02 TeV, 13 TeV pp and 5.02 TeV p+Pb, as a function of N_{ch}^{rec} (top panel). The p_{T} dependence of the v_n for the $N_{ch}^{rec} \geq 60$ multiplicity range [14] (bottom panel).

The long range correlations where extracted using approach presented in the Section 2 with muon as an associated particle. One dimensional correlation function $C(\Delta\phi)$ is obtained according to Eq. 2.2 but integrating is done over $1 < |\Delta\eta| < 5$. The template fitting method makes similar assumptions with exceptions that fit is performed to $C(\Delta\phi)$ instead of per-trigger-particle yield $Y(\Delta\phi)$. Figure 2 presents summary of the muon hadron[1] correlations with $0.5 < p_{\mathrm{T}}^{a} < 5$ Gev and $4 < p_{\mathrm{T}}^{\mu} < 6$ GeV on the left panel and for the p_{T} dependence of the muon v_2 with $4 < p_{\mathrm{T}}^{\mu} < 8$ GeV. Non-negligible values of muon v_2 was measured and it is consistent with no N_{ch}^{rec} dependence within presented uncertainties.

4. Multi-particle correlations with the subevent method

The template fitting method is suppressing the non-flow correlations impact by removing pairs with low pseudorapidity separation ($|\Delta\eta| < 2$) and fitting shape of peripheral events, where flow is assumed to be negligible. However, a multi-particle cumulant method [18] is used to reduce directly correlations from jets and dijets. Proposed approach is relying on the Q-cumulants discussed in Refs. [19, 20], which has been recently extended to the case of subevent cumulants [21]. The standard method is briefly summarized below.

The two- or four-particle azimuthal correlations in one event are evaluated as:

$$\langle\{2\}_n\rangle = \left\langle e^{in(\phi_1-\phi_2)}\right\rangle, \ \langle\{4\}_n\rangle = \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle \tag{4.1}$$

These correlation can be used to define cumulants for two- or four-particle correlations:

$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle, \ c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2 \tag{4.2}$$

[1]In practice all charged particles are used as reference particles, however since they are mostly hadrons (π, p, K) therefore the muon-hadron correlation is justified.

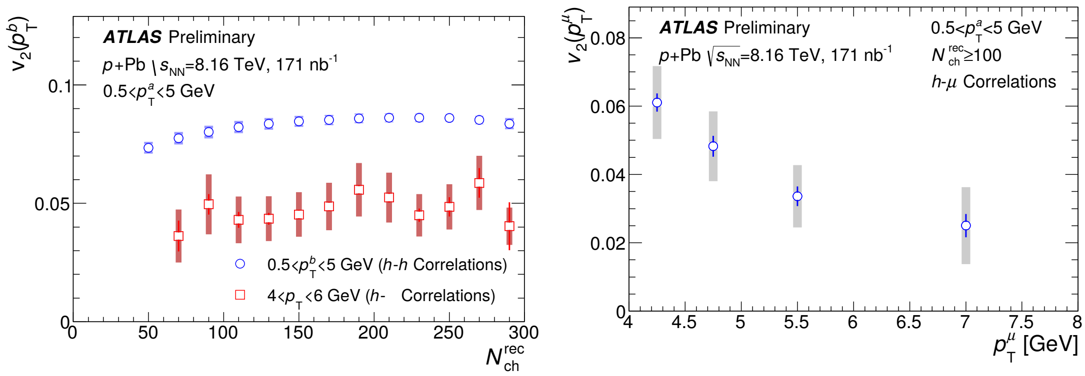

Figure 2: The v_2 obtained from the template fits to $h-h$ correlations with $0.5 < p_{\mathrm{T}}^{a,b} < 5$ GeV (circles) and to $h-\mu$ correlations with $0.5 < p_{\mathrm{T}}^{a} < 5$ Gev and $4 < p_{\mathrm{T}}^{\mu} < 6$ GeV (squares) (left panel). the p_{T} dependence of the muon v_2 integrated over a broad multiplicity range of $N_{ch}^{rec} > 100$ [17] (right panel).

Finally, the flow coefficients from two- and four-particle cumulants are defined as:

$$v_n\{2\}_n = \sqrt{c_n\{2\}},\ v_n\{4\}_n = \sqrt[4]{-c_n\{4\}} \tag{4.3}$$

To suppress the non-flow correlations, which usually involve few particles which are close each other in η, a subevent cumulant method has been proposed [21]. In this approach particles are divided into several subevents, each covering a distinct η interval and then only particles from different subevents are correlated. With three subevents the four-particle azimuthal correlations and cumulants are evaluated as:

$$\langle\{4\}_n\rangle_{2a|b,c} = \left\langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)}\right\rangle,\ c_n^{2a|b,c}\{4\} = \langle\langle\{4\}_n\rangle\rangle_{2a|b,c} - 2\langle\langle\{2\}_n\rangle\rangle_{a|b}\langle\langle\{2\}_n\rangle\rangle_{a|c} \tag{4.4}$$

The $v_2\{4\}$ obtained with the three subevent method are presented in Figure 3 for charged particles with $0.3 < p_{\mathrm{T}} < 3$ GeV in three collision systems.The $v_2\{4\}$ values are smaller than $v_2\{2\}$ from the template fit method in both systems. This difference can be interpreted as influence of event-by-event flow fluctuations associated with fluctuating initial condition [25]. More comprehensive summary can be found in [23].

5. Summary

This report summarize studies performed in four systems: 5.02 and 13 TeV pp collisions, 5.02 and 8.16 TeV p+Pb collisions by the ATLAS experiment. Measurements of v_n harmonics were performed using two methods, two particle correlation with non-flow subtraction based on templates obtained for peripheral events and a novel sub-event cumulant method. Comparisons presented in Figure 1 show that v_2, v_3 and v_4 values for 5.02 and 13 TeV pp collisions do not significantly vary with center-of-mass energy. The v_2 values obtained in pp collisions at both energies are observed to be independent of N_{ch}^{rec} within uncertainties. Measurement performed with the sub-event cumulant method show that magnitude of $v_2\{4\}$ is smaller than $v_2\{2\}$. It can be interpreted as influence of event-by-event flow fluctuations associated with fluctuating initial

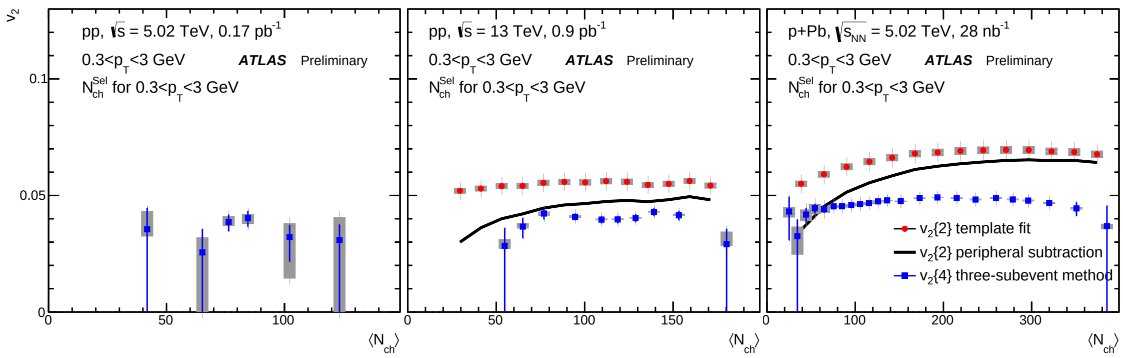

Figure 3: The $v_2\{4\}$ calculated for charged particles of $0.3 < p_T < 3$ GeV using the three subevent cumulant method in 5.02 TeV *pp* (left panel), 13 TeV *pp* (middle panel) and 5.02 TeV *p*+Pb collisions (right panel) [23]. They are compared to v_2 obtained from a two-particle correlation analysis [14, 22] where the non-flow effects are removed by a template fit procedure (solid circles) or with a fit after subtraction with zero-yield at minimum (ZYAM) assumption [24] (solid line).

condition [25]. The azimuthal muon-hadron correlation was also studied and non-negligible values of v_2 were measured.

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