NEW RESULTS ON COLLECTIVITY WITH ATLAS

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ABSTRACT

The collective phenomena are observed not only in heavy ion collisions, but also in the proton-nucleus and in high-multiplicity $pp$ collisions. The latest results from this area obtained in ATLAS are presented. In $p$+Pb collisions the emission source of particles is measured using the HBT method. The analysis of $p$+Pb data collected in 2016 provides information on the elliptic flow of charged hadrons and muons. Low multiplicity events from $pp$, $p$+Pb and peripheral Pb+Pb collisions are studied with the cumulant methods. A deeper understanding of Pb+Pb collisions is provided by the analysis of longitudinal fluctuations of the collective flow parameters.

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Figure 1: The ratio of exponential radii $R_{\text{out}}/R_{\text{side}}$ (left) as a function of the pair transverse momentum, $k_T$, in four centrality bins [2] and (right) as a function of the angular distance from the second-order event plane $2(\phi_k - \Psi_2)$ in five bins of elliptic flow vector magnitude $|q_2|$ [3]. The points for different intervals of $|q_2|$ are offset for visibility, as indicated in the legend.

1 Introduction

Strong collective effects were first found in heavy ion collisions, where they indicate a creation of the Quark-Gluon Plasma. This phase of matter manifests azimuthal correlations among produced particles, referred to as collective particle flow. However, similar effects are observed in proton-nucleus and even in high-multiplicity proton-proton collisions. The measurements of Pb+Pb, $p$+Pb and $pp$ collisions at energies available from the Large Hadron Collider (LHC) and performed using the ATLAS detector [1] allow to study collective phenomena in detail. The obtained results are important for understanding the particle production at LHC energies.

2 Results

One of the questions, which can be answered by analysing correlations among produced particles is the size of their emission source. The Bose-Einstein correlations of identical bosons, as a function of the difference of their momenta, $q = p^a - p^b$, can be parameterized as:

$$C_{\text{BE}}(q) = 1 + e^{||Rq||},$$

where the diagonal elements of the matrix $R$ are $R_{\text{out}}$, $R_{\text{side}}$ and $R_{\text{long}}$. These parameters were studied for $p$+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [2] as a function of $k_T$ (where $k = 0.5(p^a - p^b)$) and the number of nucleons participating in collisions, $N_{\text{part}}$. Especially interesting is the ratio $R_{\text{out}}/R_{\text{side}}$ which represents asymmetry of the source. In Figure 1(left) one can see that this ratio depends on $k_T$, which indicates radial expansion of the source of particles [2]. This ratio depends also on the orientation of the correlated pairs (represented by $\phi_k$, azimuthal angle of $k_T$) with respect to the event plane, $\Psi_2$, as shown in Figure 1(right). The $R_{\text{out}}/R_{\text{side}}$ ratio is larger out of plane than in plane ($\phi_k \approx \Psi_2$) as $R_{\text{out}}$ is enhanced out of plane and $R_{\text{side}}$ does not change much with $\phi_k - \Psi_2$ [3].

In the studies of azimuthal correlations among charged particles the Fourier decomposition is used:

$$\frac{dN_{\text{ch}}}{d\phi} \sim 1 + 2 \sum_{n=1}^{\infty} v_n(p_T, \eta) \cos(n(\phi - \Psi_n)).$$

The flow harmonics $v_n$ can be obtained also from two-particle correlations. In $pp$ and $p$+Pb collisions these correlations contain large contributions from other sources (non-flow), which have to be subtracted. ATLAS
Figure 2: The $v_2$ values, as a function of $N_{ch}^{\text{rec}}$, obtained (left) in $p+\text{Pb}$ collisions at 8.16 TeV and 5.02 TeV and (right) in $p+\text{Pb}$ collisions at 8.16 TeV from $h-h$ correlations (circles) and $h-\mu$ correlations (squares) [5].

Figure 3: Multiplicity dependence of (left) $v_2\{2,|\Delta\eta|>2\}$, $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$ for $p+\text{Pb}$ collisions at 5.02 TeV and low-multiplicity $\text{Pb}+\text{Pb}$ collisions at 2.76 TeV and (right) $v_2\{2,|\Delta\eta|>2\}$ for $pp$ collisions at 5.02 TeV and 13 TeV, $p+\text{Pb}$ collisions at 5.02 TeV and low-multiplicity $\text{Pb}+\text{Pb}$ collisions at 2.76 TeV [6].

applies a template method [4] to remove them. In Figure 2 the elliptic flow $v_2$ in $p+\text{Pb}$ collisions at 5.02 TeV and 8.16 TeV for all hadrons ($h-h$) and for hadron-muon ($h-\mu$) correlations (at 8.16 TeV) is shown as a function of charged-particle multiplicity, $N_{ch}^{\text{rec}}$ [5]. There is no dependence of $v_2$ on the energy of collisions and a very weak increase with multiplicity. The values of $v_2^{h-\mu}$ reach only about 0.6 $v_2^{h-h}$.

The non-flow effects are most pronounced in low-multiplicity events as they usually involve relatively small number of particles in limited kinematical range (resonance decays, jets) and are thus suppressed in multi-particle correlations. Such correlation can be used to calculate cumulants, $c_n\{2k\}$ [6], closely related to flow harmonics:

$$v_n\{2\} = \sqrt{c_n\{2\}}, \quad v_n\{4\} = \sqrt{-c_n\{4\}}, \quad v_n\{6\} = \sqrt[3]{-c_n\{6\}/4}, \quad v_n\{8\} = \sqrt[4]{-c_n\{8\}/33}. \quad (3)$$

In the case of $c_n\{2\}$ a separation of particles in pseudorapidity ($|\Delta\eta|>2$) is required in calculations of $v_n\{2,|\Delta\eta|>2\}$ to suppress short-range correlations. In Figure 3 elliptic flow $v_2$ values obtained for $p+\text{Pb}$, $\text{Pb}+\text{Pb}$ and $pp$ collisions using different multi-particle cumulants are compared [6]. While the $v_2\{2k\}$ values are similar (for $k=2, 3, 4$), those for $k=1$ with $|\Delta\eta|>2$ requirement are larger. Comparison of
Figure 4: The \( c_2\{4\} \) cumulants in \( p+Pb \) collisions at 5.02 TeV calculated for charged particles with (left) 0.3 < \( p_T < 3 \) GeV and (right) 0.5 < \( p_T < 5 \) GeV compared across the three cumulant methods \[7\].

![Figure 4: The \( c_2\{4\} \) cumulants in \( p+Pb \) collisions at 5.02 TeV calculated for charged particles with (left) 0.3 < \( p_T < 3 \) GeV and (right) 0.5 < \( p_T < 5 \) GeV compared across the three cumulant methods \[7\].](image1)

Figure 5: The \( v_2\{4\} \) values calculated for charged particles with 0.3 < \( p_T < 3 \) GeV using the three-subevent method in \( pp \) collisions at (left) 5.02 TeV, (middle) 13 TeV and (right) in \( p+Pb \) collisions at 5.02 TeV. They are compared to \( v_2 \) obtained from a two-particle correlation analysis using a template fit procedure (solid circles) or peripheral subtraction (solid line) to remove non-flow effects \[7\].

![Figure 5: The \( v_2\{4\} \) values calculated for charged particles with 0.3 < \( p_T < 3 \) GeV using the three-subevent method in \( pp \) collisions at (left) 5.02 TeV, (middle) 13 TeV and (right) in \( p+Pb \) collisions at 5.02 TeV. They are compared to \( v_2 \) obtained from a two-particle correlation analysis using a template fit procedure (solid circles) or peripheral subtraction (solid line) to remove non-flow effects \[7\].](image2)

Figure 6: The number of sources inferred from \( v_2\{2\} \) and \( v_2\{4\} \) using Eq. 4 in \( pp \) and \( p+Pb \) collisions at 13 TeV and 5.02 TeV, respectively, as a function of charged-particle multiplicity, \( N_{ch}^{Sel} \), obtained by selecting charged particles with (left) 0.3 < \( p_T < 3 \) GeV and (right) 0.5 < \( p_T < 5 \) GeV \[7\].

![Figure 6: The number of sources inferred from \( v_2\{2\} \) and \( v_2\{4\} \) using Eq. 4 in \( pp \) and \( p+Pb \) collisions at 13 TeV and 5.02 TeV, respectively, as a function of charged-particle multiplicity, \( N_{ch}^{Sel} \), obtained by selecting charged particles with (left) 0.3 < \( p_T < 3 \) GeV and (right) 0.5 < \( p_T < 5 \) GeV \[7\].](image3)
\[ v_2(2, |\Delta\eta| > 2) \] for different systems shows an increase with the size of colliding projectiles for events with the same number of produced particles. The \( v_2 \{2k\} \) harmonics do not change with the multiplicity and the energy for \( pp \) collisions while are increasing with multiplicity for \( p+Pb \) and \( Pb+Pb \) collisions.

Further suppression of short range correlations can be achieved if in the calculations of correlations, used to obtain cumulants, particles from different ranges of pseudorapidity (i.e. subevents) are used \[7\]. For \( c_2 \{4\} \) negative values are expected, as otherwise \( v_2 \{4\} \) can not be calculated using Eq. \[5\]. In Figure \[4\] one can see that positive \( c_2 \{4\} \) are obtained at low multiplicities, but are reduced in two- and especially three-subevent cumulant methods. The \( v_2 \{4\} \) values from three-subevent method are lower than \( v_2 \{2\} \) from peripheral subtraction or template fit method (Figure \[5\]). This difference can be interpreted as a result of event-by-event flow fluctuations, which are closely related to the effective number of sources, \( N_s \), for particle production:

\[
\frac{v_2 \{4\}}{v_2 \{2\}} = \left( \frac{4}{3 + N_s} \right)^{1/4}.
\]

The number of sources shown in Figure \[6\] is similar for \( pp \) and \( p+Pb \) collisions and for the latter it increases from 10 to 20 in the full available event-multiplicity range.
For events with large multiplicities, such as measured in Pb+Pb collisions at 5.02 TeV, standard methods of calculation of flow harmonics are sufficiently robust against non-flow effects. In Figure 7 (left) $v_n$, for $n = 2 – 7$, as a function of $p_T$ in 20-30% centrality interval are shown. Flow harmonics up to $v_7$ are non-zero. The $v_2$ is 0.05 even for $p_T > 20$ GeV. Relatively large $v_2$ for particles with high transverse momenta means that also very energetic partons are interacting in the QGP. This observation is consistent with the measured suppression of high-$p_T$ charged hadrons as quantified by the nuclear modification factor, $R_{AA}$.

In Figure 7 (right) one can see that $R_{AA} < 1$ in the same centrality and $p_T$ range.

A deeper understanding of flow phenomena may provide study of the dependence of flow fluctuations on position in pseudorapidity using correlators $r_{n|n;k}$ and $R_{n,n|n,n}$ (see Ref. [10] for definitions). Assuming that their dependence on pseudorapidity is linear it can be parameterized as:

$$r_{n|n;k} \approx 1 - 4 \frac{F_{n;k}}{n} \eta \quad \text{and} \quad R_{n,n|n,n} \approx 1 - 4 \frac{F_{twi}}{n} \eta,$$

where $F_{n;k} = F_{asy} + F_{twi}$, $F_{asy}$ and $F_{twi}$ are decorrelation parameters connected with magnitude (asymmetry) and twist fluctuations, respectively. In Pb+Pb collisions the decorrelation parameters $F_{n;k}$ are similar for all centralities but depend on the energy of the collision and are 10-16% larger at 2.76 TeV than at 5.02 TeV (see Figure 8 (left)). On the other hand the magnitude and twist decorrelation parameters, shown in Figure 8 (right), are approximately constant for $N_{part} > 100$. In the whole multiplicity range $F_{asy} \approx F_{twi}$ for the same $n$.

3 Conclusions

Studies of correlations among particles produced in different types of collisions available at LHC provide valuable information on properties of their source. In $p+Pb$ collisions the volume from which particles are emitted has an elongated shape and undergoes a radial expansion. The flow of muons originating from $b$ or $c$ quarks is much smaller than that of charged hadrons. Results on flow harmonics obtained using cumulant methods clearly show that the non-flow contributions are very important in low-multiplicity events and need to be properly subtracted. In new detailed studies of Pb+Pb collisions non-zero flow harmonics up to $v_7$ were measured. Analysis of longitudinal fluctuations of flow harmonics reveals decorrelation effects which are stronger at lower collision energy, but similar when decomposed into magnitude and twist contributions.

References

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