Azimuthal angle correlation measurements of charged hadrons are presented in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The second- ($v_2$) and third-order ($v_3$) Fourier harmonics are extracted using two-particle correlation and four-particle cumulant methods covering similar multiplicity ranges in pPb and PbPb over a wide range of pseudorapidity. A large four-particle $v_2$ as a function of multiplicity in pPb collisions is comparable to the PbPb system. Nearly identical two-particle correlation $v_3$ signals between the pPb and PbPb systems are observed. In ultra-central PbPb collisions, factorization of the Fourier harmonics is shown. The observed factorization breakdown is found to be consistent with the $p_T$ dependent event-by-event fluctuating event-plane angle in the hydrodynamic picture.

Studies of the collective behavior of the emitted charged particles play an important role in characterizing the underlying properties of the hot and dense matter created in high-energy collisions of protons and nuclei. The observed long-range, two-particle $\Delta\eta$-$\Delta\phi$ (pseudorapidity and azimuthal angle difference between the two particles respectively) correlations in nucleus-nucleus (AA) collisions is well known by the “ridge-like” structure at small $\Delta\phi$ (near-side) over large relative pseudorapidity $\Delta\eta$. It has been proposed that the hydrodynamic collective flow of the strongly interacting medium can lead to such long-range correlations in central and mid-central AA collisions. However, a similar long-range correlation has been observed in high final-state charged particle multiplicity events in both proton-proton (pp) $^1$ collisions and proton-lead (pPb) $^{2,3,4}$ collisions. The amplitude of such correlation in pPb collisions is strongly enhanced compared to that in pp collisions. A detailed study of the long-range correlation in pPb is presented and compared to the PbPb system in a similar multiplicity range, to provide constraints on the theoretical understanding of the particle production mechanisms.

Figure 1 shows the charged hadron $v_2$ results (top) averaged over $0.3 < p_T < 3.0$ GeV/c using two-particle correlation ($v_2\{2,|\Delta\eta|>2\}$) and four-particle cumulant ($v_2\{4\}$) methods, as a function of the offline event multiplicity ($N_{\text{trk}}$, charged particle with $p_T > 0.4$ GeV/c and $|\eta|<2.4$). An $\eta$ gap of 2 units is applied in two-particle correlation method between the trigger and associated particles to suppress non-flow contribution, such as jet fragmentation and resonance decay. Data are from semi-peripheral PbPb collisions at 50–100% centrality at a center-of-
mass energy of $\sqrt{s_{NN}} = 2.76$ GeV (left), collected during 2011, and minimum-bias and high multiplicity triggered pPb collision at $\sqrt{s_{NN}} = 5.02$ TeV, collected during 2013. The dedicated high multiplicity triggers are used during pPb data taking as an online selection of events with large amount of reconstructed tracks from a single collision. They can trigger events with multiplicity as high as equivalent to 55% centrality PbPb collisions. The $v_2\{2, |\Delta \eta| > 2\}$ and $v_2\{4\}$ values increase moderately in PbPb collisions with increasing $N_{\text{trk}}^{\text{offline}}$. These coefficients remain relatively constant for pPb data at large multiplicity. Over large range of $N_{\text{trk}}^{\text{offline}}$, the PbPb data show a larger $v_2$ signal than for pPb data. Since the $v_2$ fluctuation contributes differently to the two-particle correlation and four-particle cumulant method, the fluctuation can be then estimated from the difference of $v_2\{2\}$ and $v_2\{4\}$. If hydrodynamic flow is the dominant source of the correlations, the upper limit of the $v_2$ fluctuation can be approximated by $\sqrt{(v_2^2\{2\} - v_2^2\{4\})/v_2^2\{2\} + v_2^2\{4\}}$, which is shown in Figure 1, bottom. The $v_2$ fluctuation is systematically higher in pPb collisions than the PbPb. And it shows an increasing trend as increasing $N_{\text{trk}}^{\text{offline}}$ in pPb collisions, while it is relatively flat in PbPb.

Figure 2 shows the two-particle $v_3\{2, |\Delta \eta| > 2\}$ values for pPb and PbPb collisions using same dynamic range as Figure 1. The remarkably similar $v_3$ values for both pPb and PbPb systems at the same event multiplicity are not trivially expected within the hydrodynamic picture, because the initial geometry configurations for the two systems are very different. For both pPb and PbPb collisions, $v_3$ values increase as $N_{\text{trk}}^{\text{offline}}$ increases. It is also found that, at low multiplicity $N_{\text{trk}}^{\text{offline}} \approx 40-50$, $v_3\{2, |\Delta \eta| > 2\}$ and $v_2\{4\}$ could not be reliably extracted for both systems. The turning off of $v_3\{4\}$ might indicate the absence of the collective correlation at low multiplicity, or the breaking down of the cumulant method.

Another important goal of the heavy-ion physics program is to understand the transport properties of the hot and dense matter, particularly, the shear viscosity over entropy density ratio, $\eta/s$. It can be studied through the azimuthal anisotropy in ultra-central PbPb collisions (i.e. the top 0.2% most central collisions), where the initial-state geometry is predominantly generated by fluctuations, and various orders of eccentricities predicted by different models tend to converge. In the two-particle correlation flow measurement, it assumes that the measured two-particle correlation can be factorized into a product of the two individual single-particle azimuthal distribution, with respect to a common event-plane angle throughout the event. Any
deviation from the factorization assumption is considered to be the non-flow effect. However, it has been shown that the initial-state eccentricity fluctuations could be one possible source of factorization breakdown \(^6,^8\). The event-plane angle, \(\Psi_n\) determined by final-state particles, could depend on \(p_T\) event-by-event, instead of a common event-plane angle. Therefore, the breakdown effect can be evaluated by calculating the ratio in CMS PbPb collisions as

\[
r_n \equiv \frac{V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}})}{\sqrt{V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{trig}})V_{n\Delta}(p_T^{\text{assoc}}, p_T^{\text{assoc}})}},
\]

where \(p_T^{\text{trig}}\) and \(p_T^{\text{assoc}}\) are the transverse momentum of the trigger and associated particles. If \(V_{n\Delta}\) factorizes, \(r_n\) will be equal to unity. If an event-by-event \(p_T\) dependent event-plane presents, the ratio can be rewritten as

\[
r_n = \frac{\langle v_n(p_T^{\text{trig}}) v_n(p_T^{\text{assoc}}) \cos \left[ n(\Psi_n(p_T^{\text{trig}}) - \Psi_n(p_T^{\text{assoc}})) \right] \rangle}{\sqrt{\langle v_n^2(p_T^{\text{trig}}) \rangle \langle v_n^2(p_T^{\text{assoc}}) \rangle}},
\]

where \(\Psi_n(p_T^{\text{trig}})\) and \(\Psi_n(p_T^{\text{assoc}})\) represent the event-plane angles associated to trigger and associated particles from different \(p_T\) intervals.

Figure 3 shows the \(r_2\) values from four centrality classes (0–0.2%, 0–5%, 0–10%, 40–50%) as a function of the differences between \(p_T^{\text{trig}}\) and \(p_T^{\text{assoc}}\). The \(r_2\) values deviate from unity as the collisions become more central, and the deviation gets larger as the difference of \(p_T^{\text{trig}}\) and \(p_T^{\text{assoc}}\) increases. It reaches up to 20% in ultra-central events for \(2.5 < p_T^{\text{trig}} < 3.0\) GeV/c. This can be understood as the event-by-event initial-state fluctuations becomes dominant in more central collisions. Theoretical calculations from viscous hydrodynamics in Ref. \(^6\) are compared to the results with MC Glauber model \(^9,^{10}\) initial condition with \(\eta/s = 0.08\) (dashed lines), and MC-KLN model with \(\eta/s = 0.2\). Both models qualitatively agree with the data observations. The data favor MC-KLN model with \(\eta/s = 0.2\). However, further detailed studies of ultra-central results are needed to put a precise constrain on \(\eta/s\). Higher-order harmonics \(r_3, r_4\) can be
found in Ref. 11. The factorization is satisfied over a wider range of $p_T^{\text{trig}}$, $p_T^{\text{assoc}}$ and centrality ranges. The breakdown is about 5% for the larger values of $p_T^{\text{trig}} - p_T^{\text{assoc}}$, i.e., greater than 1 GeV/c.

In summary, the CMS collaboration has measured the two- and four-particle correlations, extracted the flow harmonics $v_2$ and $v_3$ in pPb collisions, and compared to PbPb collisions in the similar multiplicity ranges. Large $v_2$ signals in high multiplicity pPb events are observed, which are comparable to PbPb mid-central collisions. Remarkable similar $v_3$ results for pPb and PbPb collisions could not be trivially understood. Factorization breakdown in PbPb collisions provide important insight of the hot and dense matter created in the PbPb collisions.

References

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