Flow Harmonics $v_n$ in pPb and PbPb Collisions

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Abstract

Previous CMS measurements have demonstrated the collective nature of multiparticle correlations in high-multiplicity pPb collisions at the LHC. This collectivity is consistent with a hydrodynamic flow origin. However, it can also be interpreted in terms of initial state effects arising from gluon saturation. The pseudorapidity dependence of the azimuthal Fourier coefficients ($v_n$) is expected to be sensitive to the underlying mechanism with, in the hydrodynamic picture, the longer lifetime of the fireball on the Pb-going side expected to lead to a larger flow signal than found on the p-going side. To investigate the detailed properties of the observed collectivity, differential $v_n$ values in transverse momentum ($p_T$) and pseudorapidity ($\eta$) are presented over the full range of the CMS tracker detector ($-2.4 < \eta < 2.4$) for pPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. Results based on multiparticle analyses involving four or more particles are shown. An event plane analysis is presented where the influence of recently demonstrated event-plane decorrelation is considered. Comparisons are made with peripheral PbPb collisions measured at similar mid-rapidity particle multiplicities. The results will be discussed in the context of current models of the longitudinal dependence of the multiparticle correlations.

Keywords: Flow, Multiparticle Cumulant, Event Plane, Lee-Yang Zeros

1. Introduction

Recent studies of multiparticle correlations in proton on lead collisions have raised the prospect that a quark-gluon plasma droplet might be formed that exhibits fluid-like behavior [1, 2, 3, 4]. In AA collisions, the long-range two-particle correlations are attributed to the collective flow from a strongly interacting, expanding medium [5]. The detailed azimuthal angle distribution of emitted particles can be characterized by its Fourier components [6]. In particular, the second and third Fourier components, known as elliptic and triangular flow, respectively, most directly reflect the medium response to the initial collision geometry and to its fluctuations.

To provide further constraints on the theoretical understanding of the particle production mechanism in different collision systems, this analysis presents results on the pseudorapidity $\eta$ and $p_T$ dependence of flow harmonics $v_n$ from pPb and PbPb collisions using the 4-, 6- and 8-particle Q-cumulant method, the Lee-Yang Zeros (LYZ) method, and the event-plane method. Within the hydrodynamic picture, the longer lifetime of the medium for pseudorapidities on the Pb-going side in pPb collisions is expected to lead to larger values for the flow harmonics than found for the p-going side pseudorapidities [7]. The pPb system is studied at $\sqrt{s_{\text{NN}}} = 5.02$ TeV using high-statistics data obtained by the CMS experiment during the 2013 pPb run at the LHC. With a large data sample, the particle correlations have been studied in a regime of high...
multiplicity pPb collisions comparable to the particle multiplicity in mid-central (50–60% centrality) PbPb collisions. This allows for a direct comparison of pPb and PbPb systems over a broad range of high particle multiplicities, allowing for a better understanding of the multiparticle nature of the observed correlations.

2. Method

The event-plane method takes advantage of the long-range behavior by establishing an event-plane angle in one range of pseudorapidity and then measuring the correlations of particles in a different range with respect to this reference angle [8]. It can be expressed in terms of Q-vectors [9] as

\[ \vec{Q}_n = (Q_{nA}, Q_{nB}) = \left( \left| Q_n \right| \cos(n\Psi_n), \left| Q_n \right| \sin(n\Psi_n) \right) = \left( \sum_{i=1}^{M} w_i \cos(n\phi_i), \sum_{i=1}^{M} w_i \sin(n\phi_i) \right). \] (1)

where \( w_i \) is the weight to optimize the resolution. Then

\[ v_n \{ \text{EP} \} = \sqrt{\frac{\left\langle \left| Q_{nA} Q_{nB}^* \right| \right\rangle}{\left\langle \left| Q_{nA} \right| \left| Q_{nB} \right| \right\rangle}}. \] (2)

The \( Q_n \) vectors associated with the event planes A, B, and C (i.e., \( Q_{nA}, Q_{nB}, \) and \( Q_{nC} \)) are based on either transverse energy or transverse momenta measured in the respective detectors, with \( w_i(Q_{nA}) \) and \( w_i(Q_{nB}) \) taken as the transverse energy measured in calorimeters and \( w_i(Q_{nC}) \) set to the transverse momentum of the particles detected in the tracker region. It has recently been noted and now experimentally confirmed by CMS [10], that the event-plane angle should not be considered as a global observable. This angle can vary as a function of transverse momentum and pseudorapidity. The variation with pseudorapidity can have a significant effect on the harmonic coefficient values (\( v_n \)) deduced using the event-plane method. Further studies show that, taking the pseudorapidity range of event plane C same as the particle of interest (POI), i.e. \( \eta_C = \eta_{\text{POI}} \), can account for the decorrelation effect if it is a Gaussian spreading. With a “twist” type decorrelation, this technique can partially account for the effect.

The multiparticle correlation is measured using the Q-cumulant method [11]. By correlating the \( m \)-particles (\( m=4, 6, 8 \)) within the reference phase space of \( |\eta| < 2.4 \) and \( p_T \) range of \( 0.3 < p_T < 3.0 \text{ GeV}/c \), the reference flow \( v_2[m] \) can be obtained. With respect to the reference flow, the differential \( v_2[m](p_T, \eta) \) can then be derived by replacing one of the \( m \)-particle cumulants with a particle from a certain POI phase space in \( p_T \) or \( \eta \). A software library is developed to explicitly calculate such cumulants.

The LYZ method allows a direct study of the large-order behavior by using the asymptotic form of the cumulant expansion to relate locations of the zeros of a generating function to the azimuthal correlations. Further, the Lee-Yang Zeros (\( v_2[\text{LYZ}] \)) results. The two-particle correlations (\( v_2(2) \)) and 4-particle cumulant (\( v_2(4) \)) from Ref. [14] are also shown. The greater values found for \( v_2 \{ \text{EP} \} \) and \( v_2(2) \) suggest a significant, and expected, contribution of fluctuations in the initial state geometry to these results.

The effect of event-plane decorrelation with pseudorapidity can be seen in Fig. 2 by comparing the \( v_2(\text{EP})(p_T) \) results within a symmetric pseudorapidity in the center-of-mass frame (\( \eta^p \) correspond to \( 2.0 < \eta < 2.4 \), i.e. \( 1.6 < \eta_{\text{CM}} < 2.0 \), \( \eta^P \) correspond to \( -1.6 < \eta < -1.2 \), i.e. \( -2.0 < \eta_{\text{CM}} < -1.6 \), based on the two analyses with \( \eta_{C} = 0 \) and \( \eta_C = \eta_{\text{POI}} \).
The yield-weighted average $v_2$ values with $0.3 \leq p_T < 3.0$ GeV/c as a function of pseudorapidity are shown for the different analysis methods in Fig. 3. The pseudorapidity dependence is almost flat for the event-plane calculations where $\eta_C = \eta_{POI}$. This is in contrast to the event-plane results for $\eta_C = 0$ and for the higher order particle correlations analyses, where the $v_2$ values at larger pseudorapidities are significantly smaller. It is only for the event-plane analysis with $\eta_C = \eta_{POI}$ that a partial accounting for the event-plane decorrelation behavior is achieved. Both the cumulant and LYZ analyses employ integral reference flows based on the full range of the CMS tracker and thus are not able to account for decorrelation effects.

The different system dependence of $v_2$ and $v_3$ is illustrated in Fig. 4 where the event-plane results with $\eta_C = \eta_{POI}$ are shown for both systems. The $v_3$ values, believed to result from initial geometry fluctuations, are almost identical for the two systems. The $v_2$ values are likely to still reflect the lenticular shape of the collision geometry in the PbPb system, leading to larger $v_2$ coefficients than seen for the pPb system.

4. Conclusion

The $\eta$ and $p_T$ dependence of the “elliptic flow” $v_2$ coefficient is presented for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and for peripheral PbPb collisions with $\sqrt{s_{NN}} = 2.76$ TeV based on event-plane, multiparticle cumulant, and Lee-Yang Zeros analyses. The data are obtained using the CMS detector with the pseudorapidity coverage determined by the range of the CMS tracker detector, with $|\eta| < 2.4$. The pseudorapidity dependence of the “triangular flow” $v_3$ coefficient is also presented based on an event-plane analysis.

The event-plane analysis is done in both ways, accounting and not accounting event-plane decorrelation effects. Excluding the pseudorapidity decorrelation effects, little difference is found in $v_2(p_T)$ between $-2.0 < \eta_{CM} < -1.6$ and $1.6 < \eta_{CM} < 2.0$ in the range of $p_T < 2$ GeV/c. In pPb and PbPb collisions, the yield weighted $v_2$ results at comparable values of $N_{\text{trk}}$ show similar behavior, with the PbPb system values consistently about 20% higher than found for pPb collisions. No significant difference is observed for the PbPb $v_3$ values as compared to pPb collisions.
Fig. 3. $v_2$ corresponding to event-plane, cumulant, and LYZ methods as a function of $\eta$ in PbPb (left) and pPb (right) collisions for selected $N_{\text{offline}}$ ranges. The $v_2$ [EP] results are based on the furthest HF event plane in pseudorapidity. The pseudorapidities are given in the laboratory frame.

Fig. 4. Elliptic ($n=2$) and triangular flow ($n=3$) harmonics for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and PbPb at $\sqrt{s_{NN}} = 2.76$ TeV with $\eta_C = \eta_{\text{POI}}$. The $v_2$ [EP] results are based on the furthest HF event plane in pseudorapidity.

References