PROCEEDINGS OF SCIENCE

Measurement of azimuthal anisotropy at high p_{T} using subevent cumulants in pPb collisions at CMS

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The second-order (elliptic) Fourier coefficients (v_2) as a function of particle transverse momentum (p_{T}) and event multiplicity are presented for pPb collisions using a subevent multiparticle cumulant analysis where nonflow effects are strongly suppressed. The data were recorded by the CMS experiment at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. The new measurement probes an extended range of particle p_{T}, up to values where the influence of nonflow effects are shown to strongly influence the results using a standard cumulant analysis. Results for both pPb and PbPb collisions are compared in similar multiplicity ranges, allowing for an assessment of the medium influence on the elliptic anisotropy associated with high p_{T} particle production.

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1. Introduction

The observation of strong collective azimuthal correlations in relativistic nucleus-nucleus (AA) collisions at the BNL RHIC [1, 2] and CERN LHC [3, 4] facilities is believed to reflect the formation of a quark-gluon plasma (QGP) that exhibits nearly ideal hydrodynamic behavior [5]. The azimuthal correlation structure of the emitted particles can be characterized by its Fourier components. In hydrodynamic models, the second and third Fourier components, known as elliptic (v_2) and triangular (v_3) flow, respectively, reflect the response of the medium to the initial collision geometry and fluctuations, providing insights into the fundamental transport properties of the QGP medium [6]. Similar correlations have been observed in high-multiplicity proton-lead (pPb) [7, 8] collisions at the LHC, which raises the question of whether a fluid-like QGP state is also created in small hadronic collision systems. These long-range correlations have also been studied in lighter AA systems such as dAu [9] and ^{3}HeAu [10] at RHIC, with the properties of the observed long-range correlations in small systems consistent with hydrodynamic models of a tiny QGP droplet [11].

The present analysis focuses on the origin of azimuthal anisotropy at very high transverse momentum(p_T). At high p_T, partons are not expected to be thermalized in the hot and dense medium created in heavy ion collisions, and a hydrodynamic picture is not applicable. Rather, the observed azimuthal anisotropy in this regime is primarily attributed to the interaction between high-p_T partons and the QGP medium [12], which is expected to have a lenticular geometry for non-central AA collisions. As the high-p_T partons traverse through the hot and dense medium, they lose energy through induced radiation and collisional interactions with the medium constituents. This energy loss depends on the path length traversed by the partons through the medium, which in turn depends on the direction in which the partons travel relative to the orientation of this medium [13, 14]. The evidence for the formation of a QGP in pPb collisions [15, 16] makes the study of how this smaller scale medium affects high-p_T partons of considerable interest. The method used in the present analysis is based on the Q-cumulant multiparticle correlation technique [17] with subevents [18, 19]. Rapidity gaps are required between the particles in the correlators to strongly suppress short-range correlations. In this work, we present the first subevent cumulant analysis of the azimuthal anisotropy up to $p_T \sim 20$ GeV in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV. The results are compared to a similar analysis using PbPb collision events at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Both collision systems were measured using the CMS experiment at the LHC.

2. Subevent cumulants

The multiparticle Q-cumulant [17] method is used to measure the v_2 value of charged hadrons within $\eta < 2.4$ using the software package *mcorrelations* [20]. The Q-cumulant method has been used to measure 4-, 6-, and 8-particle correlations in previous CMS publications [21, 22], with the multiparticle correlations being inherently less sensitive to the few-particle correlations such as those arising from jet fragmentation and back-to-back dijet correlations. The m-particle cumulant method correlates each Particle of Interest (POI) with $m - 1$ Reference Flow Particles (RFPs). In this analysis, the RFPs for the cumulant method are charged hadrons within $\eta < 2.4$ and with $0.3 < p_{\mathrm{T}} < 3.0$ GeV (for pPb) and $0.5 < p_{\mathrm{T}} < 3.0$ GeV (for PbPb). The upper p_T bound of the

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RFP range is chosen so as to reduce the contribution of minijets, which can contribute above $p_{\mathrm{T}} \sim 3$ GeV.

In a standard multiparticle Q-cumulant analysis, the POI and RFP ranges overlap in η. In order to suppress non-flow effect from the short-range correlations, a subevent method has been suggested based on the calculations published in Ref. [18]. It has to be noted that the method and calculation are essentially the same between the regular and subevent method, but for the subevent method instead of selecting particles in the full acceptance, particles are selected from different subevents to develop the cumulant values. By selecting the correlated particles from different subevents, the contribution from short-range correlations is naturally suppressed as a pseudorapidity gap is guaranteed between any two particles in a given correlation.

In this analysis, we use p_T differential cumulants, $d_n\{4\}$, defined as

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle \cdot \langle\langle 2 \rangle\rangle, \tag{1}$$

where $\langle\langle 4' \rangle\rangle$ is 4-particle correlator with 3 RFPs and one POI and $\langle\langle 2' \rangle\rangle$ is 2-particle correlator with one RFP and one POI. In the following, we provide the formula to compute $d_n\{4\}$ in all scenarios, where a, b, c and d are refering to the particle chosen in a specific subevent and the symbol "|" indicates a separation between subevents. In Eq. 2, for example, the notation a′a|bb in the 4- particle correlator means that two particles are required to be in the first subevent (a′a) while the other two are required to be in the second subevent (bb), where a′ is the POI. Similarly, for the 2-particle correlator, one particle in each subevent is required (a′b).

The 2 subevent differential cumulant can be expressed in terms of the correlators with

$$d_n\{4\}_{2sub} = \langle\langle 4 \rangle^{a'a|b^*b^*}\rangle - 2\langle\langle 2 \rangle^{a'|b^*}\rangle \cdot \langle\langle 2 \rangle^{a|b^*}\rangle. \tag{2}$$

For the 3 subevent, the correlator expansion depends on the pseudorapidity range of POI, with

$$d_n\{4\}_{3sub} = \langle\langle 4 \rangle^{a|b^*b^*|c'}\rangle - 2\langle\langle 2 \rangle^{a|b^*}\rangle \cdot \langle\langle 2 \rangle^{b^*|c'}\rangle \tag{3}$$

when the POI is in the range $2.4 < |\eta| < 0.8$ and

$$d_n\{4\}_{3sub} = \langle\langle 4 \rangle^{a|b^*b'^*|c}\rangle - \langle\langle 2 \rangle^{a|b'^*}\rangle \cdot \langle\langle 2 \rangle^{b^*|c}\rangle - \langle\langle 2 \rangle^{a|b^*}\rangle \cdot \langle\langle 2 \rangle^{b'^*|c}\rangle \tag{4}$$

when $|\eta| < 0.8$. In the latter case, we have two choices for POI and accordingly two combinations for the product of 2-particle correlators ($\langle\langle 2 \rangle^{a|b'^*}\rangle \cdot \langle\langle 2 \rangle^{b^*|c}\rangle$ and $\langle\langle 2 \rangle^{a|b^*}\rangle \cdot \langle\langle 2 \rangle^{b'^*|c}\rangle$). Similarly, in the case of 4 subevents, instead of taking twice the product of 2-particle correlators, we have incorporated two different choices ($\langle\langle 2 \rangle^{a'|c^*}\rangle \cdot \langle\langle 2 \rangle^{b|d^*}\rangle$ and $\langle\langle 2 \rangle^{a'|d^*}\rangle \cdot \langle\langle 2 \rangle^{b|c^*}\rangle$) as

$$d_n\{4\}_{4sub} = \langle\langle 4 \rangle^{a'|b|c^*|d^*}\rangle - \langle\langle 2 \rangle^{a'|c^*}\rangle \cdot \langle\langle 2 \rangle^{b|d^*}\rangle - \langle\langle 2 \rangle^{a'|d^*}\rangle \cdot \langle\langle 2 \rangle^{b|c^*}\rangle. \tag{5}$$

The $v_n\{4\}$ value can then be expressed as

$$v_n\{4\} = -\, d_n\{4\}/(-c_n\{4\})^{3/4}, \tag{6}$$

where $c_n\{4\}$ is the integral cumulant for RFPs. Details about the CMS detector and this analysis can be found in Ref. [23].

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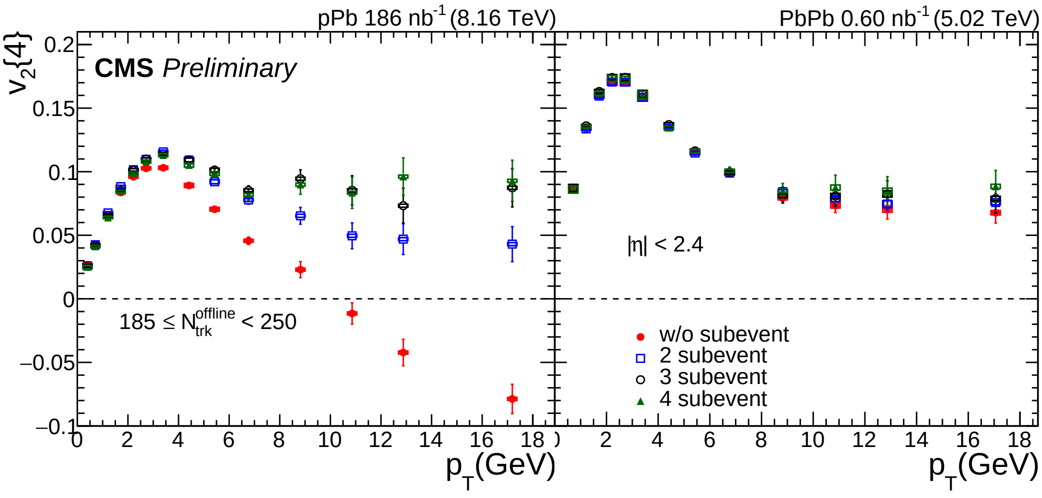

Figure 1: $v_2\{4\}$ vs p_T in $185 \leq \mathrm{N}_{\mathrm{trk}}^{\mathrm{offline}} < 250$ for pPb (Left) and PbPb (Right). Statistical uncertainty is represented by solid lines and systematic uncertainty by boxes.

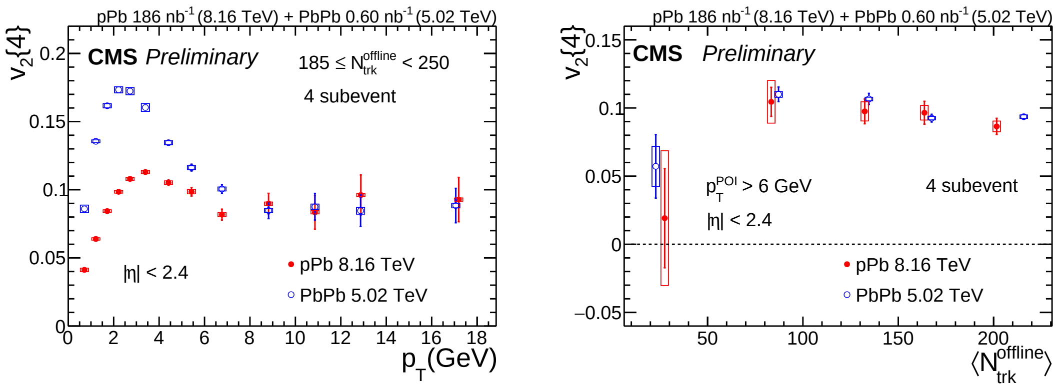

Figure 2: Left: Comparison of $v_2\{4\}$ with 4 subevent vs p_T in $185 \leq \mathrm{N}_{\mathrm{trk}}^{\mathrm{offline}} < 250$ between pPb and PbPb. Right: Comparison of $v_2\{4\}$ with 4 subevent vs $\langle \mathrm{N}_{\mathrm{trk}}^{\mathrm{offline}} \rangle$ for p_T of POI > 6 GeV between pPb and PbPb. Statistical uncertainty is represented by solid lines and systematic uncertainty by boxes.

3. Results

The $v_2\{4\}$ results for the different subevent scenarios are shown for the $185 \leq \mathrm{N}_{\mathrm{trk}}^{\mathrm{offline}} < 250$ range as a function of p_T in Fig. 1. The left panel shows the results for pPb collisions and the right panel for PbPb collisions. The standard $v_2\{4\}$ result (without subevents) goes negative after $p_\mathrm{T} \sim 10$ GeV for pPb collisions, which is not the case for the PbPb results. This could be a consequence of selecting rare high multiplicity events in the pPb events with an increased nonflow contribution from jets as compared to PbPb events. Using the subevent method, this negative trend is heavily suppressed and we get positive values of $v_2\{4\}$ (negative value of $d_2\{4\}$) up to $p_\mathrm{T} \sim 17$ GeV, the upper limit of the current investigation. The 3 and 4 subevent results are in agreement,

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suggesting complete removal of non-flow correlations. Also, 3 and 4 subevent $v_2\{4\}$ values are almost constant above $p_{\rm T} \sim 6$ GeV in both collision systems. The left plot in Fig. 2 compares the 4-subevent, $v_2\{4\}$ values as a function of p_T for pPb and PbPb collisions. We observe similar magnitude of $v_2\{4\}$ in both the collision systems at high $p_{\rm T}$. In the right plot of Fig. 2, we show the 4-subevent, $v_2\{4\}$ values for POI particles with $p_{\rm T} > 6$ GeV as a function $\langle {\rm N}_{\rm trk}^{\rm offline} \rangle$ for pPb and PbPb collisions. The magnitude and $\langle {\rm N}_{\rm trk}^{\rm offline} \rangle$ dependence of the $v_2\{4\}$ values for the two systems are very similar. For the $0 < {\rm N}_{\rm trk}^{\rm offline} < 60$ range, the $v_2\{4\}$ value is consistent with zero for pPb collisions, within the statistical and systematic uncertainties.

4. Summary

In summary, the $v_2\{4\}$ values calculated using subevents are presented for pPb and PbPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV and $\sqrt{s_{\rm NN}} = 5.02$ TeV, respectively. This analysis investigates an extended phase space region that has not been previously studied in small systems. After using a subevent method to remove nonflow correlations due to jet fragmentation, a significant and positive value for $v_n\{4\}$ is determined for higher multiplicity pPb events extending to high particle $p_{\rm T}$. A striking similarity is observed in the magnitudes of high $p_{\rm T}$ $v_2\{4\}$ values in high multiplicity pPb and peripheral PbPb collisions, suggesting a similar mechanism for the observed anisotropy at high $p_{\rm T}$ in the two systems. These results provide new information on the interaction of high-$p_{\rm T}$ partons with the surrounding medium in heavy ion collisions.

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