

Strange hadron collectivity in pPb and PbPb collisions



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ABSTRACT: The collective behavior of K_S^0 and $\Lambda/\bar{\Lambda}$ strange hadrons is studied by measuring the elliptic azimuthal anisotropy (v_2) using the scalar-product and multiparticle correlation methods. Proton-lead (pPb) collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 8.16$ TeV and lead-lead (PbPb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV collected by the CMS experiment at the LHC are investigated. Nonflow effects in the pPb collisions are studied by using a subevent cumulant analysis and by excluding events where a jet with transverse momentum greater than 20 GeV is present. The strange hadron v_2 values extracted in pPb collisions via the four- and six-particle correlation method are found to be nearly identical, suggesting the collective behavior. Comparisons of the pPb and PbPb results for both strange hadrons and charged particles illustrate how event-by-event flow fluctuations depend on the system size.

KEYWORDS: Collective Flow, Hadron-Hadron Scattering

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1 Introduction

Strong collective azimuthal correlations between particles have been observed in relativistic nucleus-nucleus collisions at the BNL RHIC [1–3] and the CERN LHC [4–9]. These correlations suggest the formation of a strongly interacting quark-gluon plasma (QGP) that exhibits nearly ideal hydrodynamic behavior [10–12]. In recent years, similar long-range collective correlations have been observed for events with high final-state particle multiplicity in both proton-proton (pp) [13–16] and proton-lead (pPb) [17–20] collisions at the LHC. These observations have prompted the question as to whether a fluid-like QGP state is also created in lighter hadronic collision systems. Such long-range correlations have also been studied at RHIC using deuteron-gold [21, 22] and helium-3-gold [23] collisions.

Hydrodynamic models provide macroscopic descriptions of a system that is in approximate local thermal equilibrium [11]. The detailed azimuthal correlation structure of emitted particles in these models is typically characterized by its Fourier coefficients [24]. In particular, the second Fourier coefficient, known as elliptic flow (v_2), most directly reflects the medium response to the initial collision geometry, and provides crucial insights into fundamental transport properties of the QGP medium [25–27]. The properties of the v_2 coefficients observed in lighter systems are consistent with hydrodynamic models of a tiny QGP droplet [28], but other explanations have also been suggested for the observed behavior. A model where gluon saturation in the initial state is assumed has been shown to capture the main features of the correlation data [29, 30]. Another suggestion is that the observed correlations arise from the anisotropic escape of partons which undergo different numbers of scatterings as they traverse the interaction region [31].

For a given collision impact parameter, event-by-event fluctuations in the initial-state geometry result in a dispersion of the v_2 values. Both the mean and variance of this distribution can be characterized by cumulants. The second-order cumulant of strange hadron v_2 in pp [16] and pPb [32, 33] collisions has been measured via long-range correlations with a pseudorapidity gap of at least two units. Here, we present measurements of higher-order cumulants of v_2 for the strange quark particles K_S^0 and Λ (generically referred to as “strange V^0 particles”), where the inclusion of the charge-conjugate $\bar{\Lambda}$ is implied. The results are presented for very high multiplicity pPb collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{NN}} = 8.16$ TeV and for lead-lead (PbPb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV, including ones with similar multiplicity to the pPb data.

The v_2 coefficients for strange V^0 particles at midrapidity ($|y| < 1$) are determined in the transverse momentum (p_T) range up to 8.5 GeV via multiparticle cumulant and scalar-product (SP) methods [34]. The SP method effectively measures the second-order cumulant of v_2 by imposing a pseudorapidity gap. The multiparticle Q -cumulant technique [35] is used to determine higher order cumulants involving more than two particles. This method has been employed in previous analyses for identified particles in PbPb collisions by the ALICE [36] and CMS [37] collaborations. In this analysis, the PbPb results are obtained in an extended range of centrality (5–80%), where centrality is defined in terms of the fraction of the total inelastic nucleus-nucleus cross section, with 0% denoting the maximum overlap of the colliding nuclei.

Differences in the 4- and 6-particle v_2 values observed for high-multiplicity pPb collisions are examined using a jet veto to suppress jet correlations, which are not related to the overall system collectivity. The results provide a quantitative measure of the jet contributions to the multiparticle correlation in pPb collisions as a function of the final-state particle multiplicity. A subevent analysis of higher-order cumulants is also presented to suppress the effect of short-range correlations in both the PbPb and pPb systems. Tabulated results are provided in the HEPData record for this analysis [38].

2 Experimental setup and data sample

The CMS detector comprises a number of subsystems. The silicon tracker, located in the 3.8 T field of a superconducting solenoid, consists of 1440 silicon pixel and 15 148 silicon strip detector modules (Phase-0). In 2017, an additional layer was added in both the barrel and endcap regions of the pixel detector and the number of silicon pixel modules increased to 1856 (Phase-1) [39]. The silicon tracker measures charged particles within the laboratory pseudorapidity range $|\eta| < 2.5$, and provides 25–90 (20–75) μm transverse impact parameter resolution in the Phase-0 (Phase-1) pixel detector and a p_T resolution better than 1.5% up to 100 GeV [40]. The electromagnetic (ECAL) and hadron (HCAL) calorimeters are also located inside the solenoid and cover the range $|\eta| < 3.0$. The ECAL consists of lead tungstate crystals arranged in a quasi-projective geometry. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates. Steel and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta| < 5.2$ on either side of the interaction region. The calorimeter cells are grouped in projective “towers”

of granularity $(\Delta\eta \times \Delta\phi) = 0.087 \times 0.087$ for the central η region used in the present jet measurement. The HF calorimeters are azimuthally subdivided into 20° modular wedges and further segmented to form 0.175×0.175 radians $(\Delta\eta \times \Delta\phi)$ towers. The detailed Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 [41]. A more detailed description of the CMS detector can be found in ref. [42].

The analysis presented in this paper uses approximately 4.27×10^9 minimum bias (MB) triggered events, corresponding to an integrated luminosity of 0.58 nb^{-1} , from PbPb collisions collected by the CMS experiment during the 2018 LHC run at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. The MB events are triggered by requiring signals above the readout threshold of 3 GeV in each of the HF calorimeters [43]. Further selections are applied offline to reject events from background processes (beam-gas interactions and nonhadronic collisions), as discussed in ref. [44]. Events are required to have at least one interaction vertex, reconstructed based on two or more tracks, with a distance of less than 15 cm from the center of the nominal interaction point along the beam axis. The primary interaction vertex is defined as the one with the highest track multiplicity in the event. For the tracks used in detecting the primary vertex, the shapes of the clusters in the pixel detector have to be compatible with those expected from particles produced at the primary vertex location. In the final analysis, the PbPb collision events are required to have at least two calorimeter towers in each HF detector with energy deposits of more than 4 GeV per tower. These criteria select $(99 \pm 2)\%$ of inelastic hadronic PbPb collisions. Finding values higher than 100% reflects the possible presence of ultra-peripheral (nonhadronic) collisions in the selected event sample. The event centrality for PbPb collisions is determined by the transverse energy deposited in the HF calorimeters [45].

The pPb data used in this analysis were recorded by CMS in 2016 and corresponds to an integrated luminosity of 186 nb^{-1} [46]. The beam energies were 6.5 TeV for protons and 2.56 TeV per nucleon for lead nuclei, resulting in $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$. A mid-run reversal of the lead and proton beam directions results in negligible differences in the detector-related systematic effects, and the merged results are reported using the convention that the proton-going direction defines positive pseudorapidity. The nucleon-nucleon center of mass in the pPb collisions is not at rest with respect to the laboratory frame because of the energy difference between the colliding particles. Massless particles emitted at $\eta_{\text{cm}} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta = -0.465$ (clockwise proton beam) or 0.465 (counterclockwise proton beam) in the laboratory frame. In this paper, an unsubscripted η symbol is used to denote the laboratory frame pseudorapidity. In order to select high-multiplicity pPb collisions, a dedicated high-multiplicity trigger was implemented using the CMS level-1 (L1) [47] and high-level trigger (HLT) systems [43]. At L1, the pPb events were triggered by requiring at least one track with $p_{\text{T}} > 0.4 \text{ GeV}$ in the pixel tracker during a pPb bunch crossing and at least one tower in one of the two HF detectors having an energy above 1 GeV. In addition, the total number of ECAL and HCAL towers with transverse energies above a threshold of 0.5 GeV is required to exceed 120 and 150 in ECAL and HCAL, respectively. The events that pass the L1 trigger are subsequently filtered by the HLT.

The track reconstruction that is performed online, as part of the HLT trigger, uses the identical reconstruction algorithm as employed in the offline processing [40]. For each pPb

event, the vertex reconstructed with the highest number of primary tracks was selected. The number (multiplicity) of primary tracks ($N_{\text{trk}}^{\text{offline}}$) with $|\eta| < 2.4$, $p_T > 0.4$ GeV, and a distance of closest approach (DCA) to this vertex of 0.4 cm or less, were determined for each event. Because of hardware limits on the data acquisition rate, a fraction of all triggered events were recorded (i.e. “prescaled”). No prescale was applied on the highest multiplicity events. In the offline analysis, hadronic collisions are selected by the requirement of a coincidence of at least one HF calorimeter tower containing more than 3 GeV of total energy in each of the HF detectors within $3.0 < |\eta| < 5.2$. Events are also required to contain at least one reconstructed primary vertex within 15 cm from the nominal interaction point along the beam axis and within 0.15 cm transverse to the beam trajectory. At least two reconstructed tracks are required to be associated with the primary vertex. Beam-related background is suppressed by rejecting events for which less than 25% of all reconstructed tracks pass the track selection criteria as above. The entire pPb data set is divided into classes of reconstructed primary track multiplicity, $N_{\text{trk}}^{\text{offline}}$, where primary tracks passing the high-purity criteria described in ref. [40] and with $|\eta| < 2.4$ and $p_T > 0.4$ GeV are counted. The HLT p_T cutoff, which is only applied in determining $N_{\text{trk}}^{\text{offline}}$, is higher than that used for the analysis because of online processing time constraints. The absence of the time constraints in the offline processing allows extending the p_T coverage down to 0.3 GeV in the analysis. The multiplicity classification ($120 \leq N_{\text{trk}}^{\text{offline}} < 150$, $150 \leq N_{\text{trk}}^{\text{offline}} < 185$, $185 \leq N_{\text{trk}}^{\text{offline}} < 250$, $N_{\text{trk}}^{\text{offline}} \geq 250$) in this analysis is identical to that used in ref. [48], where more details are provided, including a table relating $N_{\text{trk}}^{\text{offline}}$ to the fraction of MB-triggered events.

Tracks for both PbPb and pPb events must pass the high-purity selection criteria described in ref. [40]. In addition, a reconstructed track is only considered as a candidate track originating from the primary vertex if the separation along the beam axis between the track and the best matching vertex, and the track-vertex impact parameter measured transverse to the beam, are both less than three times their respective uncertainties. The relative uncertainty in the p_T measurement is required to be less than 10%.

The CMS particle-flow (PF) algorithm [49] aims to identify stable particles in an event by combining information from all subdetector systems, classifying them as electrons, muons, photons, and charged and neutral hadrons. The PF candidates are then clustered into jets using the anti- k_T sequential recombination algorithm [50] provided in the FASTJET framework [51]. The jets used in this analysis are obtained using a distance parameter $R = 0.4$. The underlying event contribution to the jet energy in pPb collisions is subtracted using an iterative procedure described in refs. [45, 52].

3 Reconstruction of K_S^0 and Λ

The reconstruction procedure for K_S^0 and Λ candidates in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is presented in ref. [32]. To increase the efficiency for tracks with low momenta and large impact parameters, both characteristic of the strange-particle decay products, a loose selection of tracks, as discussed in ref. [40], was used. The K_S^0 and Λ candidates are reconstructed by combining oppositely charged particles to define a secondary vertex. The track pair is assumed to originate from $\pi^+\pi^-$ in K_S^0 reconstruction, and π^-p ($\pi^+\bar{p}$) in the

Λ ($\bar{\Lambda}$) reconstruction. As the proton (antiproton) carries nearly all of the laboratory-frame momentum for the Λ ($\bar{\Lambda}$) decay, the higher-momentum track is assumed to be a proton (antiproton) and the other track a pion. Each of the two tracks must have hits in at least three layers of the silicon tracker, and transverse and longitudinal significances of the fitted impact parameter with respect to the primary vertex greater than 1. The significance of a quantity is defined as its value divided by its uncertainty. The distance of closest approach of the pair of tracks is required to be less than 1.0 cm.

As a result of the long lifetime of the K_S^0 and Λ particles ($c\tau > 1$ cm), the significance of the V^0 decay length, which is the three-dimensional (3D) distance between the primary and V^0 vertices, is required to exceed 2.5. To remove K_S^0 candidates misidentified as Λ particles and vice versa, the Λ (K_S^0) candidate mass, assuming both tracks to be pions (the lower-momentum track to be a pion and the higher-momentum track a proton/antiproton) must differ by more than 20 (10) MeV from the nominal K_S^0 (Λ) mass value [53]. To remove photon conversions to an electron-positron pair, the mass of a K_S^0 or Λ candidate must be higher than 15 MeV assuming both tracks to have the electron mass. The angle θ^{point} between the V^0 momentum vector and the vector connecting the primary and V^0 vertices is required to satisfy $\cos \theta^{\text{point}} > 0.999$. This reduces the contributions of particles from nuclear interactions, random combinations of tracks, and secondary Λ particles originating from the weak decays of Ξ and Ω particles.

The final selection of strange V^0 candidates for PbPb collisions is performed via multivariate discriminators to enhance the efficiency and signal-to-background ratio, based on a boosted decision tree (BDT) method from the TMVA package [54]. The selection is optimized separately for K_S^0 and Λ candidates. The discriminating variables employed include: the collision centrality, the V^0 candidate p_T , rapidity, DCA, 3D decay length, $\cos \theta^{\text{point}}$, the fitted 3D vertex χ^2 , the 3D fitted decay vertex significance, the V^0 daughter track p_T , uncertainty in p_T , η , the number of hits in the silicon tracker, the number of pixel detector layers with hits, and the transverse and longitudinal DCA significances of the daughter tracks. The BDT training is performed employing the HYDJET 1.8 event generator [55] with full detector simulation of both the signal (strange V^0) and random combination of hadrons as background (combinatorial) candidates. The total average efficiency of detecting K_S^0 (Λ) using the BDT method is 1–3 (1–2)% from most central to peripheral PbPb collisions. Figure 1 shows examples of the invariant K_S^0 and Λ mass distributions in the p_T interval 2.8–3.6 GeV for 10–30% centrality in PbPb collisions. The K_S^0 mass window is taken between 0.430 and 0.565 GeV and the Λ mass window is taken between 1.08 and 1.16 GeV. The true V^0 signal peak is well described by a double Gaussian function with a common mean, while the background is modeled by a fourth-order polynomial function fitted over the entire mass range. The mass window of $\pm 2\sigma$ wide around the center of the peak is defined as the “peak region,” where σ represents the standard deviation of the sum of the two Gaussian distributions. To estimate the contribution of background candidates in the peak region to the correlation measurement, a “sideband region” is chosen that includes V^0 candidates from outside the $\pm 3\sigma$ mass range around the V^0 mass to the boundaries of the mass distribution windows.

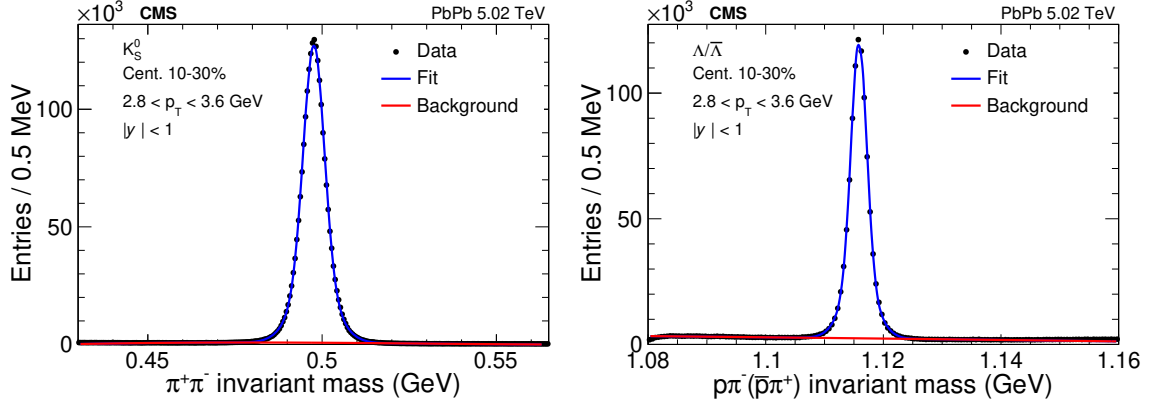


Figure 1. Invariant mass distributions of K_S^0 mesons (left) and Λ baryons (right) candidates within $|y| < 1$ and $2.8 < p_T < 3.6$ GeV in 10–30% centrality PbPb collisions at 5.02 TeV. The blue lines show the fitted signal peak. The red lines indicate the fitted background component.

The reconstruction and cut-based selection procedures for the strange V^0 candidates in pPb collisions are identical to those in refs. [32, 56]. Pairs of oppositely charged particle tracks that are detached from the primary vertex (i.e., having large significance of the impact parameters) are selected to determine if they point to a common secondary vertex from the decay of a strange V^0 candidate. The difference in the cut-based and multivariate selections was found to be significant only for more central ($< 30\%$ centrality) PbPb events with $N_{\text{trk}}^{\text{offline}}$ values well above those in the pPb events studied in this analysis and, hence, only a cut-based selection was used for the pPb events.

4 Analysis techniques

The scalar-product [34] and multiparticle Q -cumulant [35, 57] methods are used to study the elliptic flow v_2 of charged hadrons within $|\eta| < 1.0$ and V^0 particles within rapidity $|y| < 1.0$. The analysis is similar to that discussed in refs. [58, 59]. The SP method uses the HF detectors to determine Q -vectors defined by reference flow particles (RFP) that have a large pseudorapidity gap ($\Delta\eta$) from the analyzed charged hadrons or strange V^0 particles of interest (POI). Two Q -vectors are calculated using the HF detectors in either the p-going (p-SP) or Pb-going (Pb-SP) direction. This method results in the same v_2 values as a two-particle correlation analysis with a large $\Delta\eta$ gap. The gap, here with $|\Delta\eta| > 2$, reduces the contributions of nonflow short-range correlations, such as jet fragmentation, the correlation of back-to-back dijets, and resonance decay. The Q -cumulant method has been used to measure 4-, 6-, and 8-particle correlations in previous CMS publications [58, 60], 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. Differences in the higher-order cumulants are also sensitive to initial-state effects that can lead to a non-Gaussian distribution of flow vectors. The m -particle cumulant method correlates each POI (strange V^0 or charged particles) with $m - 1$ RFPs (charged hadrons). In this analysis, the RFPs for the cumulant method are charged hadrons within $|\eta| < 2.4$ and with $0.5 < p_T < 5.0$ GeV.

For the strange V^0 particles, the v_2 values are first extracted from the peak region, which contains small contributions from the combinatorial background, and sideband regions, denoted as v_2^{obs} and v_2^{bkg} , respectively. The v_2 signal of the true V^0 particles is denoted by v_2^{sig} and is obtained by

$$v_2^{\text{sig}} = \frac{v_2^{\text{obs}} - (1 - f^{\text{sig}})v_2^{\text{bkg}}}{f^{\text{sig}}}, \quad (4.1)$$

where f^{sig} represents the signal yield fraction in the peak region determined by the fit to the mass distributions. The v_2^{sig} and v_2^{bkg} values are assumed to be independent of each other.

Nonflow behavior is more obvious in the small collision system because of the relatively low multiplicities involved. The jet correlations reduce the multiparticle cumulant $v_2\{m\}$ ($m = 4, 6, 8$) values [61]. While the jet correlations increase the two-particle correlation $v_2\{\text{SP}\}$ results, the large $\Delta\eta$ applied in this analysis minimizes this effect. To investigate the relative importance of the jet correlations in pPb collisions, a jet veto study is performed by rejecting events in the cumulant analyses with at least one jet with $p_T > 20$ GeV and within $|\eta| < 2.0$.

In a standard multiparticle Q -cumulant analysis, the POI and RFP overlap in η . In order to suppress nonflow effects from the short-range correlations in the multiparticle cumulant measurements, a separate analysis is performed where a pseudorapidity gap is imposed between the POI and the RFP [62]. To implement this gap, the subevent method is used, where the POI and the RFP are selected in nonoverlapping η ranges. In this analysis, the POI is selected to have $0 < y < 1$ ($-1 < y < 0$) for V^0 or $0 < \eta < 1$ ($-1 < \eta < 0$) for charged hadrons, while the RFP is selected for charged hadrons with $-2.4 < \eta < 0$ ($0 < \eta < 2.4$). The large underlying event contributions in PbPb data make it both impractical and unnecessary to apply a jet veto.

5 Systematic uncertainties

The sources of systematic uncertainties for the V^0 analysis in PbPb collisions include reconstruction requirements (BDT selections) and the primary vertex position. The systematic uncertainties for the charged hadrons in PbPb collisions are also taken to include the primary vertex positions and track quality requirements similar to ref. [58]. The uncertainties are quoted relative to the v_2 values. No centrality or p_T dependence is found for the PbPb collision results.

The BDT cutoffs have been varied up and down by 5% to account for the systematic uncertainties associated with the deviations between the simulation and experimental results. A 3% systematic uncertainty is quoted by comparing to the V^0 BDT nominal cutoffs in PbPb collisions. The uncertainties related to the V^0 background mass modeling are investigated by using an exponential or a third-order polynomial fit, and the mass spectrum of same-sign hadron pairs as background distribution, instead of the default fourth-order polynomial fit. A 1% systematic is quoted for the effects related to the background modeling. We vary the signal yield fraction f^{sig} up and down by 3% to account for the BDT training variable differences between the simulation and data. This results in a 2% systematic uncertainty in the final results. The systematic uncertainties in the primary vertex position along the

beam direction (z_{vtx}) have been studied by performing the analysis in different z_{vtx} ranges. The systematic uncertainties are estimated as 1% for charged hadrons, 2% for K_S^0 mesons, and 4% for Λ baryons. For the charged-hadron results, the potential systematic uncertainty related to the track selection criteria is investigated by varying the criteria as described in ref. [58], and a 1% systematic uncertainty is quoted.

The systematic uncertainties in pPb collisions are studied for the V^0 reconstruction (2.0%), effects of multiple collisions at the same bunch crossing (0.5%), trigger bias (1.0%), and the reconstruction of primary vertex position (1.0%). A total systematic uncertainty of 2.5% is quoted. More details can be found in ref. [56]. For the jet veto results, we estimate the systematic uncertainties related to the PF jet energy scale and jet energy resolution effects. For the jet energy scale, we take a conservative estimate of 5% variation of the cutoff value, rejecting events with jet $p_T > 21$ GeV and compare the results with the nominal 20 GeV threshold. No significant difference is observed. The jet energy resolution was parameterized as shown in ref. [63] for pp collisions. The effect of jet energy resolution was studied by applying an additional 20% uncertainty to the jet p_T , and no significant effect for a majority of multiplicity and p_T ranges on the v_2 results was found.

6 Results

The midrapidity v_2 results for charged hadrons within $|\eta| < 1.0$, and K_S^0 and Λ particles within $|y| < 1.0$ are shown for PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in figure 2, and for pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV in figure 3. The greater values found for $v_2\{\text{SP}\}$ than for the multiparticle flow coefficients at low p_T are consistent with the expectation of the event-by-event fluctuation of the elliptic flow observable. The event-by-event iEBE-VISHNU model calculations [64] with A Multi-Phase Transport (AMPT) initial conditions [65], which combine (2+1)-D viscous hydrodynamics of the QGP expansion with a cascade model of the hadron resonance gas evolution for PbPb collisions, are compared to the data up to $p_T = 3$ GeV and found to be qualitatively consistent. The AMPT model assumes each individual parton has a Gaussian initial energy density profile. The hydrodynamic v_2 values extracted using 2-particle correlation and 4-particle cumulant methods are qualitatively consistent with data in PbPb collisions. For the pPb collisions, the $v_2\{\text{SP}\}$ results with respect to the Pb- and p-going side Q-vectors are presented separately. For $p_T > 3$ GeV, the p-going Q-vector leads to systematically larger $v_2\{\text{SP}\}$ values, suggesting a larger nonflow contribution. These v_2 results are consistent with those observed in previous pPb measurements at 5.02 TeV [58].

For the pPb collisions at 8.16 TeV, a separation of the charged-hadron $v_2\{4\}$ and $v_2\{6\}$ values becomes obvious for lower $N_{\text{trk}}^{\text{offline}}$ values and at higher p_T , as shown in figure 3. The previous pPb results at 5.02 TeV [58] were limited in statistical significance and did not allow for the difference between the $v_2\{4\}$ and $v_2\{6\}$ values to be clearly established. The observed difference can be attributed to jet-related nonflow correlations, which reduce the values of both $v_2\{4\}$ and $v_2\{6\}$. Indeed, the $v_2\{6\}$ values are expected to be less affected by the jet correlations than the $v_2\{4\}$ values because they involve more particles in the calculation, reducing the influence of few-particle correlations.

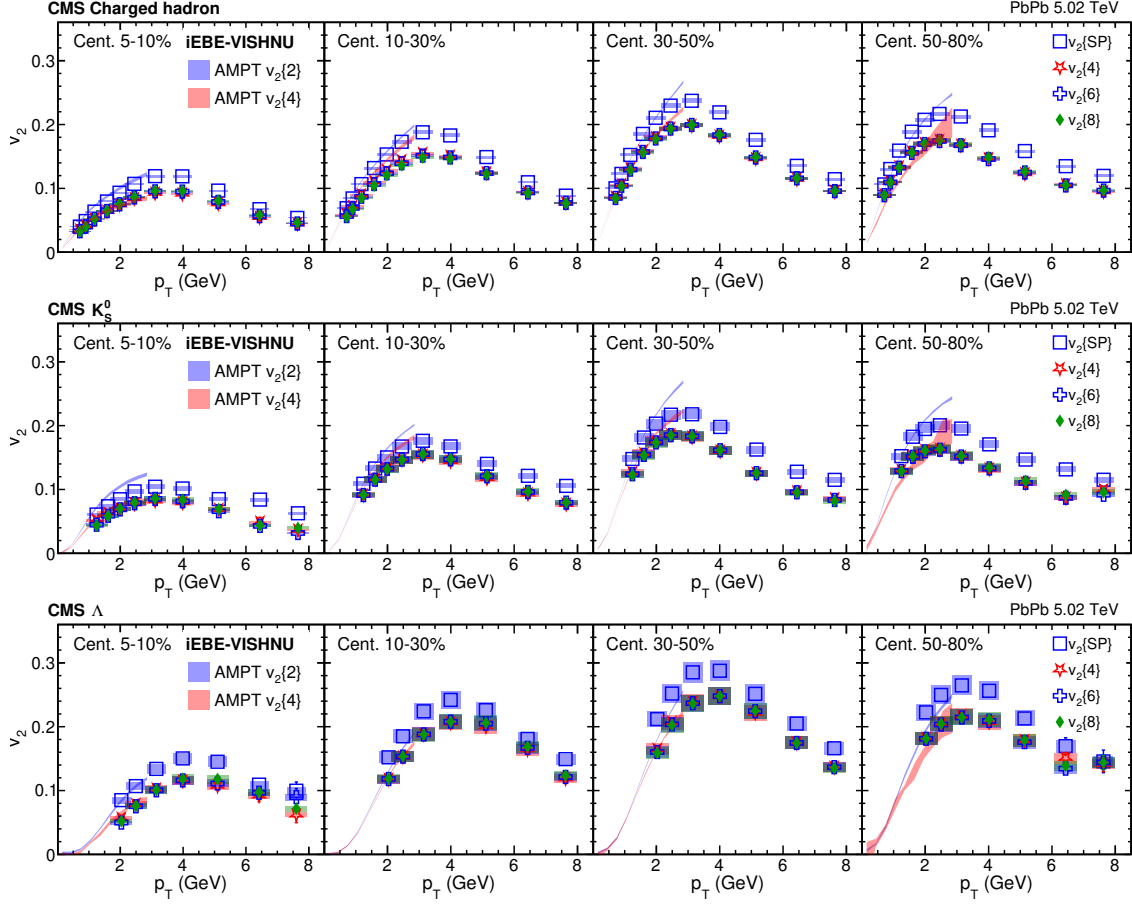


Figure 2. The scalar-product and multiparticle cumulant v_2 results of PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for charged hadrons (upper), K_S^0 mesons (middle), and Λ baryons (lower) in different centrality intervals. The shaded bands are hydrodynamic calculations of $v_2\{2\}$ and $v_2\{4\}$ values with AMPT initial conditions. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

To investigate the effect of jet correlations, events with one jet with $p_T > 20$ GeV are rejected from the pPb collision sample, leading to the results reported in figure 4. After rejecting the jet events, the 4-particle cumulant $v_2\{4, \text{veto}\}$ value is higher than the inclusive $v_2\{4\}$ value for $p_T > 3$ GeV. These results indicate that the standard 4-particle cumulant is affected by the jet-related nonflow correlations for all $N_{\text{trk}}^{\text{offline}}$ ranges at high p_T , with the influence increasing with decreasing multiplicity as shown in the ratio plots, where the uncertainties are treated as completely correlated. In contrast, the $v_2\{6\}$ and $v_2\{6, \text{veto}\}$ results are consistent, indicating that the influence of nonflow effects is very small in standard 6- and 8-particle cumulant measurements for the studied multiplicity ranges. The $v_2\{4, \text{veto}\}$ and $v_2\{6, \text{veto}\}$ values are similar for all $N_{\text{trk}}^{\text{offline}}$ ranges, which suggests that, with the jet veto, the jet-related nonflow correlations have been largely removed in the $v_2\{4, \text{veto}\}$ results.

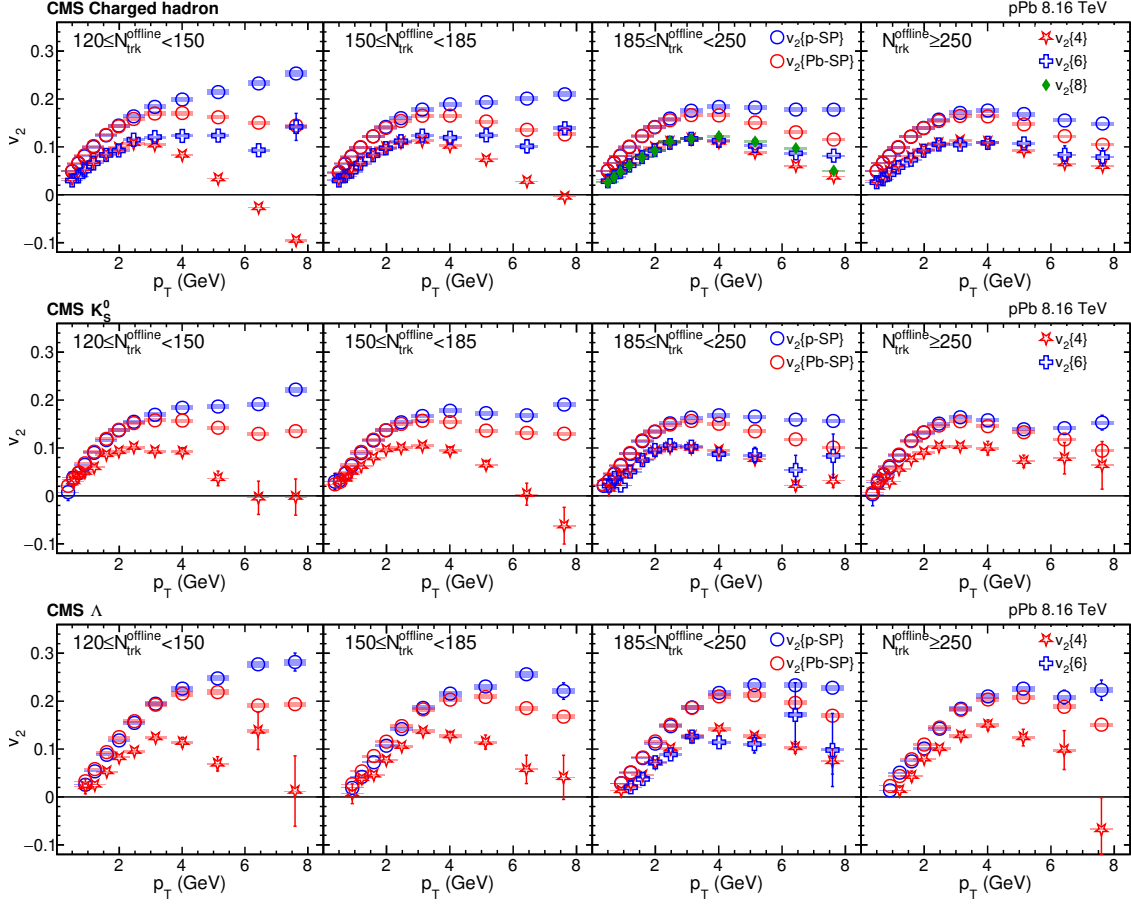


Figure 3. The scalar-product and multiparticle cumulant v_2 results of pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV for charged hadrons (upper), K_S^0 mesons (middle), and Λ baryons (lower) in different $N_{\text{trk}}^{\text{offline}}$ ranges. The scalar-product results are based on Q-vectors that are determined in either the p-going (p-SP) or Pb-going (Pb-SP) side HF calorimeter. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

The subevent 4-particle cumulant results $v_2\{4, \text{Sub}\}$ are compared to the standard $v_2\{4\}$ values in figure 5 for charged hadrons and V^0 particles in PbPb collisions. Also shown for pPb collisions are the V^0 standard and subevent 4-particle v_2 results for $185 \leq N_{\text{trk}}^{\text{offline}} < 250$, which corresponds to the multiplicity of about 62% peripheral PbPb collisions [48]. In the mid-central PbPb collisions (10–50% centrality), very good agreement is observed between $v_2\{4\}$ and $v_2\{4, \text{Sub}\}$ values, while a small disagreement is seen in the central (5–10% centrality) and the peripheral (50–80% centrality) collisions. A larger effect is observed in pPb collisions. Figure 6 shows the charged-hadron subevent 4-particle results for different $N_{\text{trk}}^{\text{offline}}$ ranges in pPb collisions.

The $v_2\{4, \text{Sub}\}/v_2\{4\}$ ratios for charged hadrons, K_S^0 mesons, and Λ baryons are shown in figure 7 for pPb and PbPb collisions. In PbPb collisions with centrality in the range of 10 to 80%, the subevent $v_2\{4, \text{Sub}\}$ values are a few percent smaller than the standard $v_2\{4\}$ values, without having an obvious p_T or particle species dependence. A larger reduction

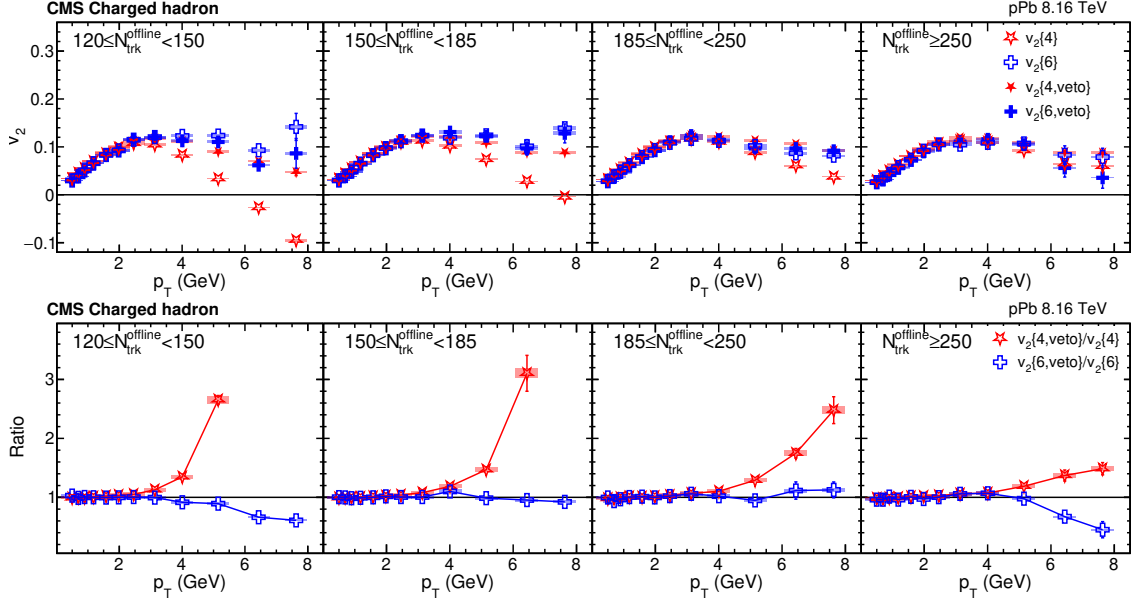


Figure 4. The charged-particle $v_2\{4\}$ and $v_2\{6\}$ distributions for pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with and without rejecting jet events (upper) and their ratios (lower) in different $N_{\text{trk}}^{\text{offline}}$ ranges. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

of up to 10% is found for the 5–10% centrality results. In pPb collisions, the $v_2\{4, \text{Sub}\}$ values are smaller than the standard $v_2\{4\}$ values by as much as 50% for higher p_T charged hadrons. The pPb identified particle results could only be obtained for the high-statistics $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ range. In this range, no strange-quark species dependence is evident. While the jet veto cumulant $v_2\{4, \text{veto}\}$ values are higher than those observed in the standard method, an opposite trend is observed by applying the subevent cumulant method. The $v_2\{4, \text{Sub}\}$ values are consistently lower than those from the standard method, inconsistent with the expectation of nonflow effects being suppressed by imposing η gaps among particles. This might reflect the decorrelation effect of the rapidity gap between the POI and RFP, which is more significant in small collision systems [66].

The difference between the scalar-product v_2 , as compared to the multiparticle correlation results, is likely to reflect initial-state fluctuation effects. Event-by-event fluctuations in the location of the participant nucleons can have a large and method-dependent influence on the harmonic coefficients [67, 68]. Expressing the fluctuations in terms of the azimuthal anisotropy in the participant plane v_2 , the magnitude of the fluctuations is given by $\sigma^2 \equiv \langle v_2^2 \rangle - \langle v_2 \rangle^2$. At the leading order, the scalar-product and multiparticle cumulant correlations $v_2\{m\}$ ($m = 4, 6$) are affected differently, with [67, 68]

$$\begin{aligned}
 v_2\{\text{SP}\}^2 &= \langle v_2^2 \rangle = \langle v_2 \rangle^2 + \sigma^2, \\
 v_2\{4\}^2 &= \sqrt{2\langle v_2^2 \rangle^2 - \langle v_2^4 \rangle} \approx \langle v_2 \rangle^2 - \sigma^2, \\
 v_2\{6\}^2 &= \sqrt{(\langle v_2^6 \rangle - 9\langle v_2^4 \rangle \langle v_2^2 \rangle + 12\langle v_2^2 \rangle^3)/4} \approx \langle v_2 \rangle^2 - \sigma^2.
 \end{aligned}
 \tag{6.1}$$

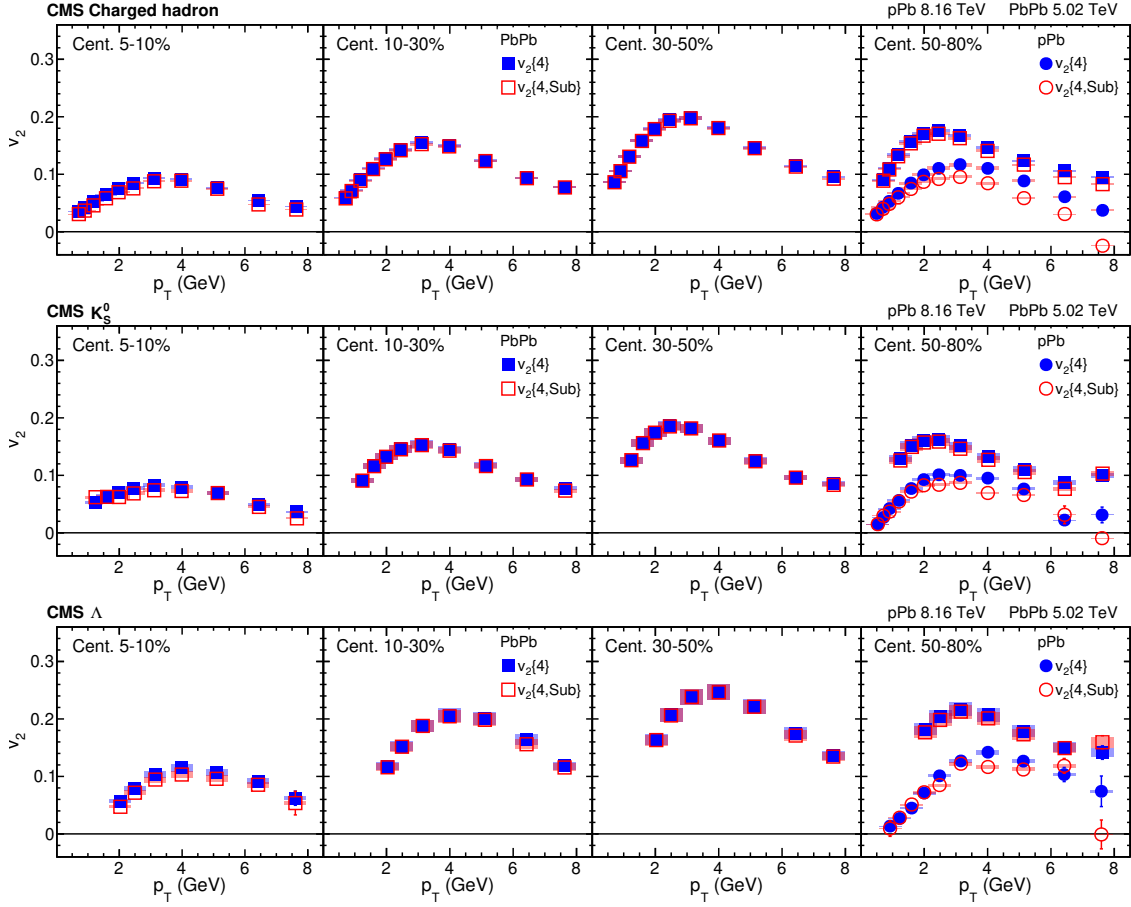


Figure 5. The standard 4-particle $v_2\{4\}$ and subevent 4-particle $v_2\{4, \text{Sub}\}$ values from PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV for charged hadrons (upper), K_S^0 mesons (middle), and Λ baryons (lower) in different centrality intervals. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

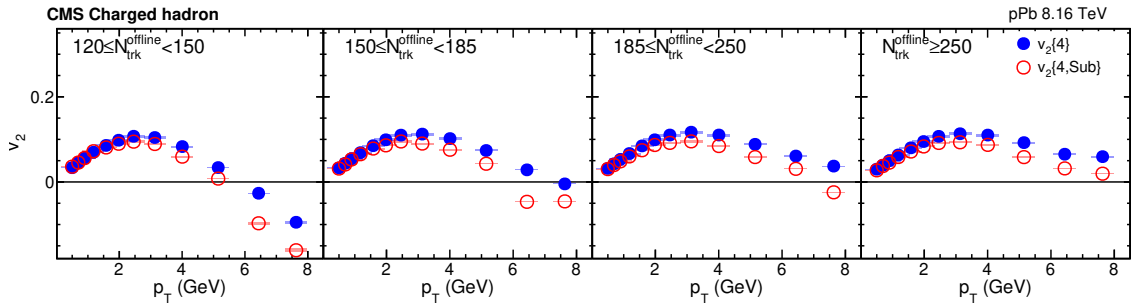


Figure 6. The $v_2\{4\}$ and $v_2\{4, \text{Sub}\}$ values from pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV for charged hadrons in different $N_{\text{trk}}^{\text{offline}}$ ranges. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

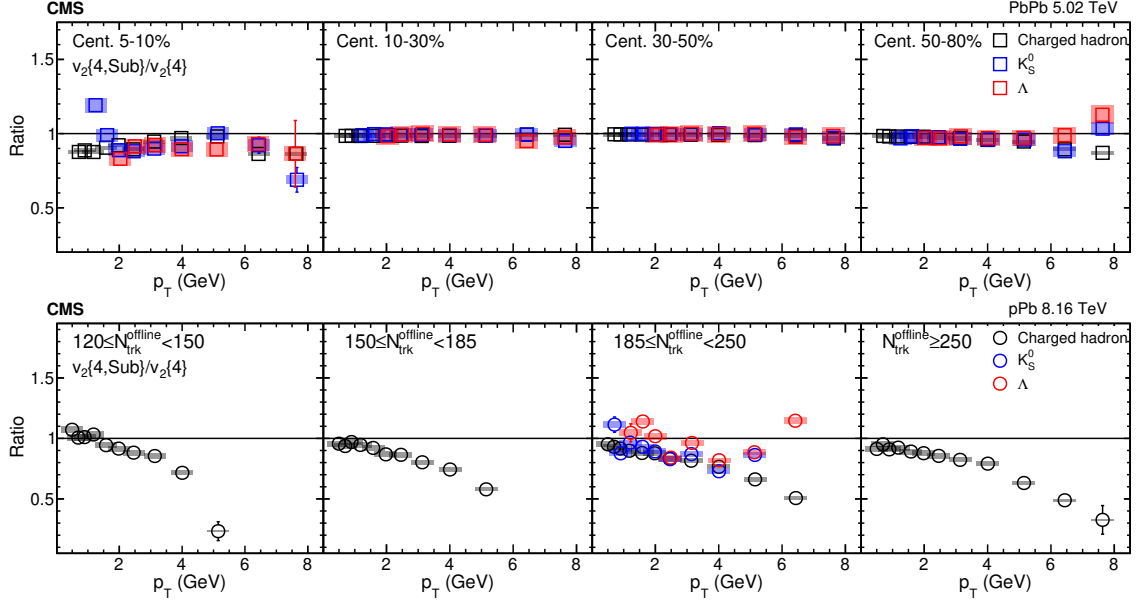


Figure 7. The $v_2\{4, \text{Sub}\}/v_2\{4\}$ ratios for charged hadrons, K_S^0 mesons and Λ baryons, for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in different centrality intervals (upper) and pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in different $N_{\text{trk}}^{\text{offline}}$ ranges (lower). The vertical bars and shaded boxes show the statistical and systematic uncertainties.

The fluctuation ratio $\sigma/\langle v_2 \rangle$ can then be calculated from $v_2\{4\}$, $v_2\{6\}$, and $v_2\{4, \text{veto}\}$ coefficients as

$$\begin{aligned}
 \frac{\sigma}{\langle v_2 \rangle} &= \sqrt{\frac{v_2\{\text{SP}\}^2 - v_2\{4\}^2}{v_2\{\text{SP}\}^2 + v_2\{4\}^2}} \\
 &= \sqrt{\frac{v_2\{\text{SP}\}^2 - v_2\{6\}^2}{v_2\{\text{SP}\}^2 + v_2\{6\}^2}} \\
 &= \sqrt{\frac{v_2\{\text{SP}\}^2 - v_2\{4, \text{veto}\}^2}{v_2\{\text{SP}\}^2 + v_2\{4, \text{veto}\}^2}}.
 \end{aligned} \tag{6.2}$$

The fluctuation ratios of charged hadrons, K_S^0 mesons, and Λ baryons are shown in figure 8 for PbPb in different centrality intervals and compared to those in pPb collisions with $185 \leq N_{\text{trk}}^{\text{offline}} < 250$. The Pb-going side Q-vector $v_2\{\text{Pb-SP}\}$ is used for pPb collisions. The fluctuations in pPb collisions are systematically higher than those in PbPb collisions for identified particles and charged hadrons. No clear particle species dependence is observed for either PbPb or pPb collisions, suggesting such fluctuations arise from the fluctuations of initial-state geometry. In PbPb collisions, the fluctuation results for both strange V^0 particles and charged hadrons are relatively flat over the measured p_T ranges. In pPb collisions, the fluctuations are lowest with $p_T \sim 3$ GeV, and approach unity at both low and high p_T . The iEBE-VISHNU hydrodynamic calculations for PbPb collisions are also shown with the AMPT and TRENTo initial conditions [69]. The TRENTo model is optimized to explain experimental results by adjusting a parameterization of the initial entropy density.

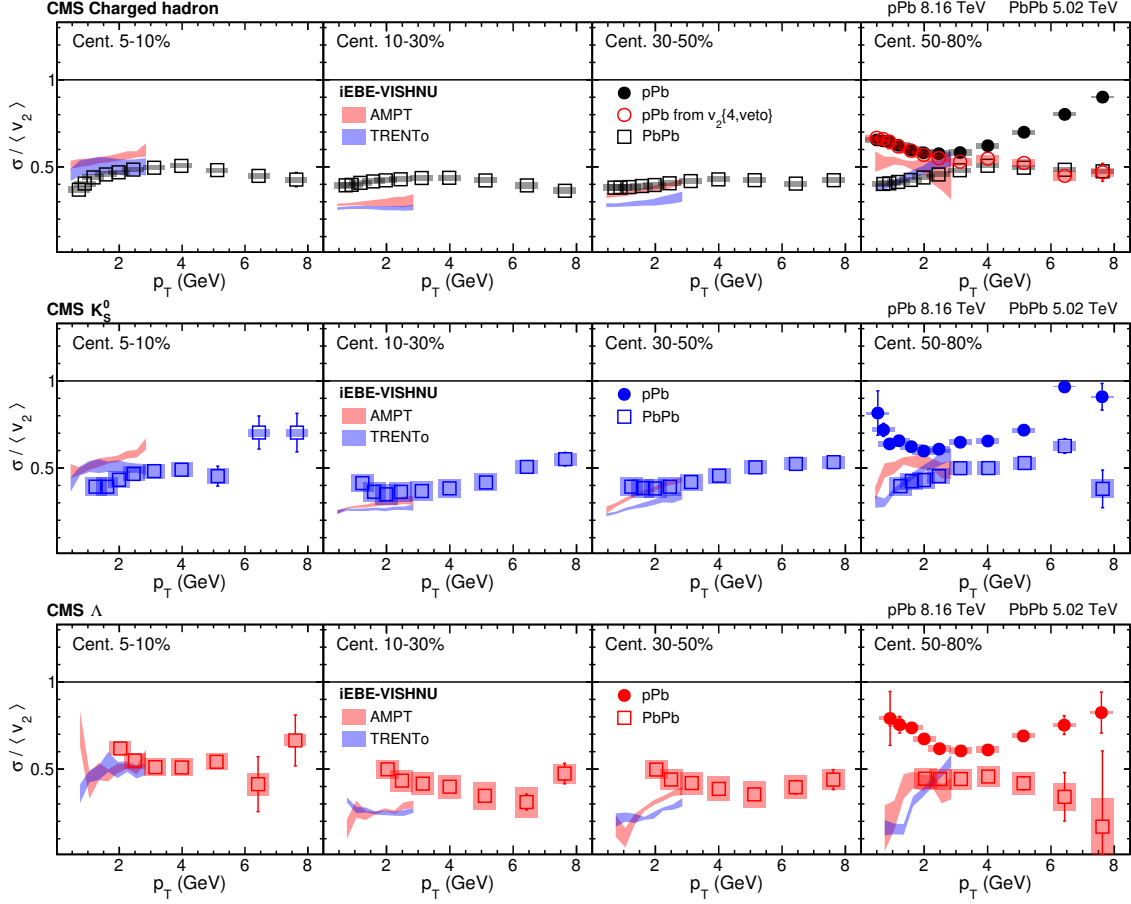


Figure 8. The v_2 fluctuation results for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in different centrality intervals and pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ using $v_2\{\text{Pb-SP}\}$ for charged hadrons (upper), K_S^0 mesons (middle), and Λ baryons (lower). The shaded bands are hydrodynamic calculations of v_2 fluctuations with AMPT and TRENTo initial conditions in PbPb collisions [64]. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

Qualitatively consistent with the data, the model calculations show little dependence on p_T . In pPb collisions, the charged hadron flow fluctuations calculated from $v_2\{4\}$, $v_2\{6\}$, and $v_2\{4, \text{veto}\}$ coefficients are compared in figure 9. The flow fluctuations at high p_T are affected by the jet correlations. If such jet-related nonflow is suppressed by 6-particle correlations, or by the jet veto method, the high- p_T flow fluctuations of charged hadrons in pPb collisions become compatible with those in the peripheral PbPb collisions.

Assuming Gaussian fluctuations of the flow harmonics, the 4-, 6- and 8-particle correlations should converge, $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$. The differences between $v_2\{6\}$, $v_2\{8\}$, and $v_2\{4\}$ indicate deviation from Gaussian fluctuation behavior for the measured particles in PbPb collisions. The $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{4\}$ ratios are shown in figure 10 for charged hadrons, K_S^0 mesons, and Λ baryons. For centrality greater than 30%, the ratios are independent of p_T and consistent with unity for the studied particle species.

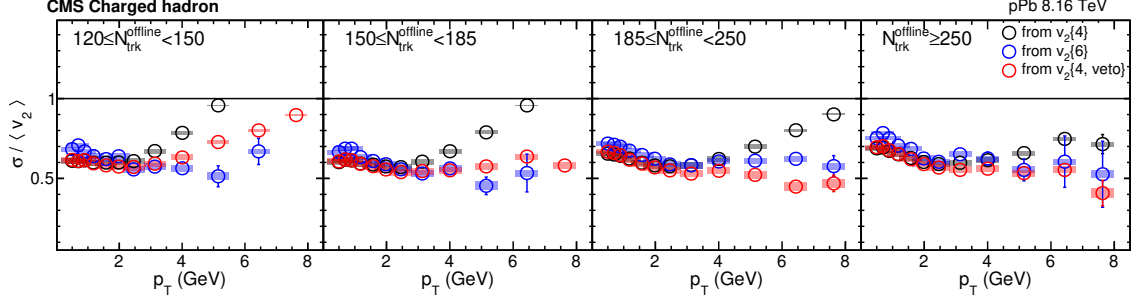


Figure 9. The v_2 fluctuation results of pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV for charged hadrons derived from different multiparticle correlations in different $N_{trk}^{offline}$ ranges. The vertical bars and shaded boxes show the statistical and systematic uncertainties.

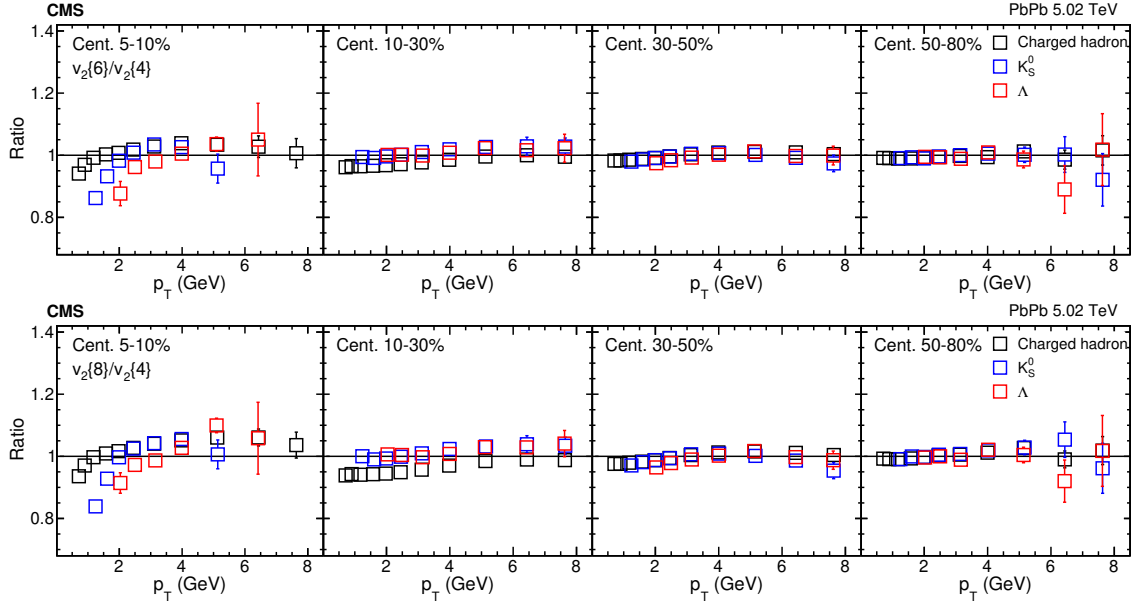


Figure 10. The $v_2\{6\}/v_2\{4\}$ (upper) and $v_2\{8\}/v_2\{4\}$ (lower) ratios in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for charged hadrons, K_S^0 mesons, and Λ baryons in different centrality intervals. The vertical bars show the statistical uncertainties. The uncertainties are treated as uncorrelated for the ratios.

7 Summary

The elliptic azimuthal anisotropy v_2 values have been measured using the scalar-product and the multiparticle Q -cumulant methods for K_S^0 mesons, Λ baryons, and charged hadrons in lead-lead (PbPb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV and high-multiplicity proton-lead (pPb) collisions at $\sqrt{s_{NN}} = 8.16$ TeV. For the first time, multiparticle correlations of identified strange particles have been studied for pPb collisions. The hydrodynamic model calculations of scalar-product $v_2\{SP\}$ and 4-particle $v_2\{4\}$ values for K_S^0 mesons, Λ baryons and charged hadrons using different initial conditions are found to be qualitatively consistent with the observations in PbPb collisions. No obvious particle species dependence of the fluctuations in the v_2 values is observed for either the PbPb or pPb systems, indicating an origin

of observed v_2 fluctuations from the initial-state geometry. The flow fluctuations are observed to be larger in pPb collisions at low transverse momentum (p_T). However, once jet correlations are removed, the pPb fluctuations are similar to those observed in peripheral PbPb collisions at high p_T .

Nonflow effects are studied for the multiparticle cumulant results. A large difference between the 4- and 6-particle v_2 values in pPb collisions that is not present for PbPb collisions can be explained by jet-related correlations. These nonflow correlations are suppressed by rejecting events with at least one jet with $p_T > 20$ GeV. A subevent cumulant method is also performed to reduce short-range correlation effects in pPb and PbPb collisions. Whereas the jet rejection study results in higher values for $v_2\{4\}$ as compared to the standard method, the subevent method leads to smaller values. This difference may be attributed to the effect of flow decorrelations on the subevent cumulant method.

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