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Non-Gaussian elliptic-flow fluctuations in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

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Abstract

Event-by-event fluctuations in the elliptic-flow coefficient v_2 are studied in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ using the CMS detector at the CERN LHC. Elliptic-flow probability distributions $p(v_2)$ for charged particles with transverse momentum $0.3 < p_{\mathrm{T}} < 3.0\,\mathrm{GeV}/c$ and pseudorapidity $|\eta| < 1.0$ are determined for different collision centrality classes. The moments of the $p(v_2)$ distributions are used to calculate the v_2 coefficients based on cumulant orders 2, 4, 6, and 8. A rank ordering of the higher-order cumulant results and nonzero standardized skewness values obtained for the $p(v_2)$ distributions indicate non-Gaussian initial-state fluctuation behavior. Bessel–Gaussian and elliptic power fits to the flow distributions are studied to characterize the initial-state spatial anisotropy.

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*See Appendix A for the list of collaboration members

1 Introduction

Ultrarelativistic heavy ion collisions at both the BNL RHIC and the CERN LHC create a hot and dense state of matter that consists of strongly interacting quarks and gluons, the so-called "quark-gluon plasma" (QGP) [1–6]. Measurement of azimuthal particle correlations indicate that this plasma has a collective behavior that is described well by hydrodynamic models [7], with a shear viscosity to entropy density ratio η/s that is of the order of the lowest possible value for a quantum fluid [8, 9]. Fluctuations in the initial-state transverse energy density affect the azimuthal correlations. Properties of the created medium can be deduced by studying these fluctuation effects. In particular, precision studies of the small differences that can occur in the moments of the Fourier components of the azimuthal behavior, as found in measurements of multiparticle correlations of different numbers of particles, can help constrain the geometry and origin of the fluctuation behavior and disentangle the initial-state effects from the subsequent evolution of the medium [10, 11]. Previous studies have suggested a two-dimensional Gaussian fluctuation behavior, leading to little dependence of the flow harmonics on the number of particles used for their determination [12–14]. Here, an event-by-event analysis is performed where it is possible to reduce the sensitivity of the results to nonflow correlations [15] and to clearly establish non-Gaussian components in the fluctuation behavior, thus developing a new window into this behavior.

The anisotropies associated with the initial-state energy density are transformed by the hydrodynamic evolution into anisotropies in the final-state momentum space for the emitted particles [16, 17]. These, in turn, are reflected in an azimuthally anisotropic distribution of the final-state particles that can be characterized by a Fourier expansion in the azimuthal angle of the measured charged particles,

$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n\phi - \Phi_n\right). \tag{1}$$

Here, the nth-order flow vector $\vec{v}_n \equiv (v_n \cos\Phi_n, v_n \sin\Phi_n)$ is determined with a phase angle Φ_n with respect to the intrinsic nth-order flow symmetry plane, as determined by the geometry of the participant nucleons. The experimentally accessible "event plane" angle is based on the direction of maximum outgoing particle density. The event plane angle is, on average, in the same direction as Φ_n, but fluctuates about Φ_n because of resolution effects due to finite particle multiplicities.

While the final-state particle distribution is characterized by the $\vec{v}_n$ coefficients, the initial-state spatial anisotropy can be characterized by an harmonic expansion in terms of vectors $\vec{\varepsilon}_n$ [18]. Fluctuations in the initial-state transverse energy density lead to event-by-event differences in the orientation and magnitude of the $\vec{\varepsilon}_n$ vectors with respect to the "reaction plane," defined by the collision impact parameter and beam directions. The presence of a nonzero viscosity will degrade the correspondence between initial- and final-state anisotropies [7, 19]. Still, a near-linear dependence is expected for the lowest order $n = 2$ (elliptic) and $n = 3$ (triangular) harmonics, with $v_n = k_n\, \varepsilon_n$ [20]. Here, $v_n \equiv |\vec{v}_n|$, $\varepsilon_n \equiv |\vec{\varepsilon_n}|$, and k_n is the flow response coefficient. In this linear-response case, it is possible to directly relate the probability distribution of the magnitudes of the $\vec{\varepsilon}_n$ vectors, $p(\varepsilon_n)$, to the corresponding $p(v_n)$ distribution:

$$p(v_n) = \frac{\mathrm{d}\varepsilon_n}{\mathrm{d}v_n}\, p(\varepsilon_n) = \frac{1}{k_n}\, p\left(\frac{v_n}{k_n}\right), \tag{2}$$

where the k_n term is expected to depend on the hydrodynamic evolution of the medium [21, 22].

The $p(v_n)$ distributions can be characterized using the experimentally determined multiparticle cumulant flow harmonics $v_n\{m\}$ [23, 24], where m is the cumulant order. Alternatively, flow distributions can be determined directly, as shown by the ATLAS Collaboration [15] and as done here, by removing finite-multiplicity resolution effects in the measured $p(v_2^{\text{obs}})$ distributions through an unfolding technique. The cumulant harmonics are expressed in terms of the moments of the $p(v_n)$ distributions [25, 26]:

$$\begin{aligned} v_n\{2\}^2 \equiv& \mathrm{E}(v_n^2), \\ v_n\{4\}^4 \equiv& -\mathrm{E}(v_n^4) + 2\mathrm{E}(v_n^2)^2, \\ v_n\{6\}^6 \equiv& \left(\mathrm{E}(v_n^6) - 9\mathrm{E}(v_n^4)\mathrm{E}(v_n^2) + 12\mathrm{E}(v_n^2)^3\right)/4, \\ v_n\{8\}^8 \equiv& -(\mathrm{E}(v_n^8) - 16\mathrm{E}(v_n^6)\mathrm{E}(v_n^2) - 18\mathrm{E}(v_n^4)^2 \\ &+ 144\mathrm{E}(v_n^4)\mathrm{E}(v_n^2)^2 - 144\mathrm{E}(v_n^2)^4)/33, \end{aligned} \tag{3}$$

where $\mathrm{E}(v_n^k) \equiv \int v_n^k p(v_n)\mathrm{d}v_n$. The unitless standardized skewness of a probability distribution is a measure of the asymmetry about its mean. For elliptic flow, the standardized skewness with respect to the reaction plane can be estimated using the cumulant flow harmonics as [27]:

$$\gamma_1^{\text{exp}} \equiv -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{\left(v_2\{2\}^2 - v_2\{4\}^2\right)^{3/2}}. \tag{4}$$

Hydrodynamic calculations find this estimate to be in good agreement with the actual skewness except for the most peripheral events [27].

The standardized skewness estimate vanishes for fluctuations that arise from an isotropic Gaussian transverse initial-state energy density profile. In this case, the $p(v_n)$ distribution is found by taking an integral over the azimuthal dependence of the two-dimensional Gaussian function [25, 28], leading to

$$p(v_n) = \frac{v_n}{\delta_{v_n}^2} \exp\left[-\frac{v_n^2 + \langle v_n^{\text{RP}}\rangle^2}{2\delta_{v_n}^2}\right] I_0\left(\frac{v_n\langle v_n^{\text{RP}}\rangle}{\delta_{v_n}^2}\right), \tag{5}$$

where $\langle v_n^{\text{RP}}\rangle$ is the average v_n value with respect to the experimentally inaccessible reaction plane angle, δ_{v_n} is the width of the distribution, and I_0 is the modified Bessel function of the first kind. For Gaussian fluctuations, the higher order, even cumulant coefficients $v_n\{m\}$ with $m \geq 4$ are degenerate and are equal to $\langle v_n^{\text{RP}}\rangle$ [25]. The observation for PbPb collisions that $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ [12–14] suggests that the $\vec{v}_2$ fluctuations can be approximately described by a two-dimensional Gaussian function [25].

Still, non-Gaussian fluctuations are expected in the initial-state energy density [27], which should lead to differences in the higher order cumulant coefficients. Such differences have been detected in the peripheral PbPb elliptic flow by the ATLAS Collaboration [14]. The precision of the LHC measurements allows for these differences to be explored in detail, giving a new method to investigate the initial-state behavior. The elliptic power function has been suggested as a formalism that can describe the asymmetric behavior of the $p(\varepsilon_n)$ distributions [10, 11]. This function is based on the assumption that the initial energy density profile of the collision is a superposition of N point-like, independent sources. In terms of the harmonic-flow coefficients and assuming a linear response,

$$p(v_n) = \frac{2\alpha v_n}{\pi k_n^2}(1-\varepsilon_0^2)^{\alpha+1/2} \int_0^{\pi} \frac{(1 - v_n^2/k_n^2)^{\alpha-1}\mathrm{d}\phi}{(1-\varepsilon_0 v_n \cos\phi/k_n)^{2\alpha+1}}, \tag{6}$$

where ε_0 is approximately equal to the mean eccentricity in the reaction plane and α, which is approximately proportional to N, describes the size of the eccentricity fluctuations.

In this Letter, the $p(v_2)$ distributions for charged particles in the pseudorapidity range $|\eta| < 1.0$ and with transverse momenta $0.3 < p_T < 3.0\,\text{GeV}/c$ are presented for PbPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ collected with the CMS detector at the LHC. The results are shown in bins of centrality, defined as fractions of the total inelastic hadronic cross section, where 0% corresponds to the events with the greatest hadronic activity in the forward direction ($|\eta| > 3.0$). The elliptic-flow harmonic values for different cumulant orders are determined based on the moments of the $p(v_2)$ distributions, with these results used to estimate the standardized skewness of the flow distribution. Elliptic power and Bessel–Gaussian fits to the flow distributions are presented to gain further insight into the initial-state fluctuation behavior.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Hadron forward calorimeters (HF) extend the pseudorapidity coverage provided by the barrel and endcap detectors to $3.0 < |\eta| < 5.2$ and are used to both select events for analysis and determine centrality. The HF calorimeters are azimuthally subdivided into 20° modular wedges and further segmented to form $0.175 \times 10°$ ($\Delta\eta \times \Delta\phi$) towers. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles of $1 < p_T < 10\,\text{GeV}/c$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) distance of closest approach [29]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [30].

3 Event and track selection

This analysis is based on a PbPb minimum bias data set corresponding to an integrated luminosity of 26 μb^{-1}, collected in 2015 . The minimum-bias trigger used requires coincident signals in the HF calorimeters at both ends of the CMS detector with energy deposits above a predefined energy threshold of approximately 1 GeV and the presence of both colliding bunches at the interaction point as determined using beam pickup timing monitors. By requiring colliding bunches, events due to noise (e.g., cosmic rays and beam backgrounds) are largely suppressed. Events are further selected offline by requiring at least three towers with an energy above 3 GeV in each of the two HF calorimeters. The primary vertex for each event is chosen as the reconstructed vertex with the largest number of associated tracks. Primary vertices are required to have at least two associated tracks and to be located within 15 (0.2) cm of the nominal collision point along the longitudinal (transverse) direction. To suppress contamination from events with multiple collisions (pileup), the procedure outlined in Ref. [6] is followed. Here, compatibility scores based on the number of pixel clusters with widths compatible with particles originating from each primary vertex are determined and events with primary vertices with compatibility scores below a predefined threshold are rejected as pileup. The mean number of collisions per bunch crossing for the events used in this analysis was $\approx$0.001.

Track reconstruction [29, 31] is performed in two iterations to ease the computational load for high-multiplicity central PbPb collisions. The first iteration reconstructs tracks from signals ("hits") in the silicon pixel and strip detectors compatible with a trajectory of $p_{\mathrm{T}} > 0.9\,\mathrm{GeV}/c$. These tracks are required to be consistent with the primary vertex, having a longitudinal association significance (d_z/σ_{d_z}) and a distance of closest approach significance (d_0/σ_{d_0}) each less than 3. In addition, the p_{T} resolution [29, 31] for each track, $\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}}$, is required to be less than 10% and tracks are required to have at least 11 out of 14 hits along their trajectory in the pixel and strip trackers. To reduce the number of misidentified tracks, the chi-squared per degree of freedom, χ^2/dof, associated with fitting the track trajectory through the different pixel and strip layers must be less than 0.15 times the total number of layers with hits along the trajectory of the track. The second iteration reconstructs tracks compatible with a trajectory of $p_{\mathrm{T}} > 0.2\,\mathrm{GeV}/c$ using solely the pixel detector. These tracks are required to have longitudinal association significance $d_z/\sigma_{d_z} < 8$ and a fit χ^2/dof value less than 12 times the number of layers with hits along the trajectory of the track. In the final analysis, first iteration tracks with $p_{\mathrm{T}} > 1.0\,\mathrm{GeV}/c$ are combined with pixel-detector-only tracks with $p_{\mathrm{T}} < 2.4\,\mathrm{GeV}/c$ after removing duplicates. Track reconstruction for the merged iterations has a combined geometric acceptance and efficiency exceeding 60% for $p_{\mathrm{T}} \approx 1.0\,\mathrm{GeV}/c$ and $|\eta| < 1.0$. When the track p_{T} is below $1\,\mathrm{GeV}/c$, the acceptance and efficiency steadily drops, reaching approximately 40% at $p_{\mathrm{T}} \approx 0.3\,\mathrm{GeV}/c$.

4 Analysis technique

The event-by-event v_2 coefficients and phases in Eq. (1) can be estimated with

$$\begin{aligned} v_{2,x}^{\mathrm{obs}} &= |\vec{v}_2^{\,\mathrm{obs}}| \cos\left(2\Psi_2^{\mathrm{obs}}\right) = \langle \cos\left(2\phi\right) \rangle = \frac{\sum_i w_i \cos\left(2\phi_i\right)}{\sum_i w_i}, \\ v_{2,y}^{\mathrm{obs}} &= |\vec{v}_2^{\,\mathrm{obs}}| \sin\left(2\Psi_2^{\mathrm{obs}}\right) = \langle \sin\left(2\phi\right) \rangle = \frac{\sum_i w_i \sin\left(2\phi_i\right)}{\sum_i w_i}, \\ |\vec{v}_2^{\,\mathrm{obs}}| &= \sqrt{\left(v_{2,x}^{\mathrm{obs}}\right)^2 + \left(v_{2,y}^{\mathrm{obs}}\right)^2}, \end{aligned} \tag{7}$$

where ϕ_i is the azimuthal angle of the track, Ψ_2^{obs} is the event plane angle defined by the direction of maximum particle density in the transverse plane, the angular brackets denote an efficiency weighted average over all particles in a given range of phase space for an event, and $w_i = 1/\varepsilon_i$ is the inverse of the tracking efficiency $\varepsilon_i\,(p_{\mathrm{T}}, \eta)$ of the i^{th} track. The analysis does not require the explicit calculation of the event plane angle for each event. In the absence of particle correlations unrelated to the hydrodynamic flow behavior ("nonflow"), the observed event-by-event flow vectors of Eq. (7) will approach the true underlying flow vectors as the particle multiplicity becomes large. In addition to the efficiency weighting, a standard recentering procedure [32], where the event average x- and y-components of the flow vector are required to equal zero, is applied to further suppress acceptance biases.

Events are sorted into different centrality classes, as determined by the transverse energy deposited in the HF calorimeters [6], and the magnitudes of the estimated flow vectors are used to construct the "observed" $p(v_2^{\mathrm{obs}})$ distributions for each class. Finite particle multiplicities result in a statistical fluctuation of the v_2^{obs} estimate for a given event about the true underlying v_2 value by a response function $p(v_2^{\mathrm{obs}}|v_2)$. This, in turn, results in a $p(v_2^{\mathrm{obs}})$ distribution that is broader than the underlying $p(v_2)$ behavior. The observed distribution can be expressed as a convolution of the underlying flow behavior and the response function

$$p(v_2^{\mathrm{obs}}) = p(v_2^{\mathrm{obs}}|v_2) * p(v_2). \tag{8}$$

A data-based technique, first introduced by the ATLAS Collaboration [15], was used to build the response function in Eq. (8). This technique divides the full event sample into two symmetric subevents (a and b) based on pseudorapidity. Given that $v_2(\eta)$ is symmetric about $\eta = 0$ on average for the symmetric PbPb system, the physical flow signal cancels in the distribution of flow vector differences from each subevent $p(\vec{v}_n^a - \vec{v}_n^b)$. The resulting distribution contains residual effects from multiplicity-related fluctuations and nonflow effects [33] and provides a basis for building the response function.

To unfold the effects of multiplicity-related fluctuations, the D'Agostini iterative method with early stopping (regularization) [34–36] was used to obtain a maximum likelihood estimate of the underlying $p(v_2)$ behavior. The analysis was done using the RooUnfold [37] package of the Root data analysis framework [38]. The unfolding procedure becomes increasingly sensitive to statistical fluctuations when the number of iterations is allowed to run to large values, resulting in unphysical oscillations in the low event count tails of the unfolded distribution. The regularization criterion used to suppress these oscillations is to apply the response function to each unfolding iteration ("refolding") and compare the resulting distribution to the observed distribution. Iterations are stopped when the χ^2/dof between the refolded and observed distribution is approximately equal to one. After this final unfolding iteration is reached, the resulting distribution is truncated above $\langle v_2 \rangle + 4\sigma_{v_2}$ to further suppress any residual artifacts in the tails that result from the unfolding procedure. Representative final unfolded distributions are shown in Fig. 1. In addition, $p(v_2^{\text{obs}})$ distributions are plotted for each centrality to illustrate the statistical resolution effects present prior to unfolding. The fits shown in Fig. 1 are discussed in Section 6.

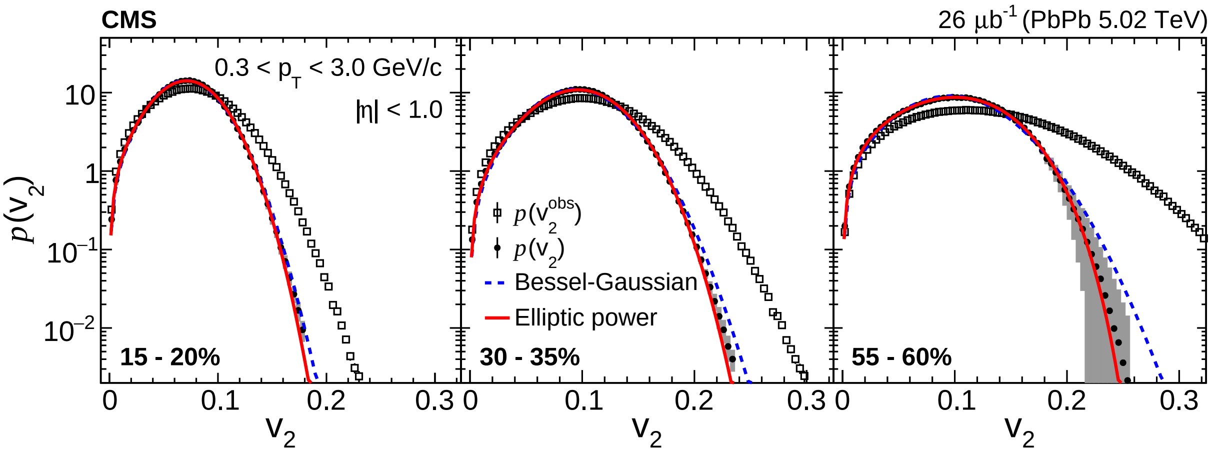

Figure 1: Representative final unfolded $p(v_2)$ distributions (closed black circles) in three centrality bins (15–20%, 30–35%, and 55–60%) obtained using D'Agostini iteration unfolding. Respective observed $p(v_2^{\text{obs}})$ distributions (open black squares) are shown to illustrate the statistical resolution present in each centrality bin prior to unfolding. Systematic uncertainties from the unfolding procedure are presented as shaded bands. Distributions are fitted with Bessel–Gaussian (dashed blue lines) and elliptic power (solid red lines) functions to infer information on the underlying $p(\varepsilon_2)$ distributions.

5 Systematic uncertainties

There are five primary sources of systematic uncertainties for the quantities extracted from the unfolded $p(v_2)$ distributions: the vertex position dependence, the response function uncertainty, the pileup contamination, the unfolding regularization, and the effect of misidentified tracks. Separate studies were done for each cumulant order, the ratios of the elliptic flow harmonic found for different cumulant orders, the standardized skewness γ_1^{exp}, and the elliptic power fit parameters. The systematic uncertainties that arise from the vertex z position are investigated by splitting the default vertex range into two windows of $|z_{\text{vtx}}| < 3.0\,\text{cm}$ and $3.0 < |z_{\text{vtx}}| < 15.0\,\text{cm}$ and comparing the results from the two ranges. To estimate the systematic uncertainty in the choice of response function, unfolding is repeated using an analytic response function obtained from a Gaussian fit to the data-driven statistical resolution distribution [15]. To assess the potential bias from residual pileup events, the threshold for determining pileup events is raised to decrease the probability of including events with multiple collisions in the analysis. The bias from unfolding regularization is studied by modifying the χ^2/dof goodness-of-fit regularization criteria and comparing the cases when the refolding χ^2/dof cutoff is 2.0 relative to when it is 1.0. To test the potential bias that might result from the 4σ truncation of the final unfolded distributions, the truncation point was varied between 3.5σ and 4.5σ. No significant bias was found in varying the truncation point. To estimate the bias from misidentified tracks, the track quality criteria described in Section 3 are varied in two scenarios that will increase and decrease the probability of misidentifying a track, respectively. The dominant uncertainties arise from the track quality criteria that affect the misidentified track contribution. Total systematic uncertainties are obtained by adding the contribution from each source in quadrature. The v_2 values calculated for the different cumulant orders have a total systematic uncertainty of the order of 5% for central collisions, which decreases to 1% in mid-central collisions. Systematic uncertainties that are correlated between different cumulant orders cancel in their ratios, leading to a total systematic uncertainty of the order of 1% for the ratios for central collisions, which decreases to 0.1% in mid-central collisions. The standardized skewness is very sensitive to small fluctuations in the cumulant flow harmonics, resulting in a systematic uncertainty of the order of 100% for central collisions that reduces to 20% for mid-central collisions.

6 Results

The cumulant elliptic-flow harmonics obtained from the moments of the unfolded $p(v_2)$ distributions using Eq. (3) are shown in Fig. 2 for cumulant orders 2, 4, 6, and 8. It was not possible to obtain reliable results for the 0–5% centrality range because of the smallness of the flow signal. The cumulant results exhibit the previously observed $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ behavior. The centrality-dependent ratios for the elliptic-flow coefficients obtained for different cumulant orders are shown in Fig. 3. For most centrality ranges, the ratios indicate a rank ordering of the cumulants, with differences on the order of a few percent and with $v_2\{4\} > v_2\{6\} > v_2\{8\}$, that is qualitatively inconsistent with a pure Gaussian fluctuation model of flow harmonics. The calculated $v_2\{6\}/v_2\{4\}$ ratio based on an event-by-event hydrodynamic calculation using Monte Carlo Glauber initial conditions [39] and an η/s value of 0.08 is shown by the shaded band. This simulation is for pions with $0.2 < p_{\text{T}} < 3.0\,\text{GeV}/c$ in PbPb collisions at $\sqrt{s_{_{\text{NN}}}} = 2.76\,\text{TeV}$ [27]. Also shown are results from the ATLAS Collaboration [14] for PbPb collisions at 2.76 TeV and for charged particles with $0.5 < p_{\text{T}} < 20.0\,\text{GeV}/c$ and $|\eta| < 2.5$. The calculation is consistent with the experimental results found at both beam energies. The similarity between experimental results with 2.76 and 5.02 TeV is consistent with the small changes in the initial state eccentricities expected between these energies [40].

Figure 4 shows the centrality dependence of the standardized skewness γ_1^{exp}. Nonzero values are found for the standardized skewness for centrality bins that that show unequal higher order cumulants. The hydrodynamic predictions for the γ_1^{exp} values for PbPb collisions at 2.76 TeV from Ref. [27] are also shown and found to be consistent with the current measurements.

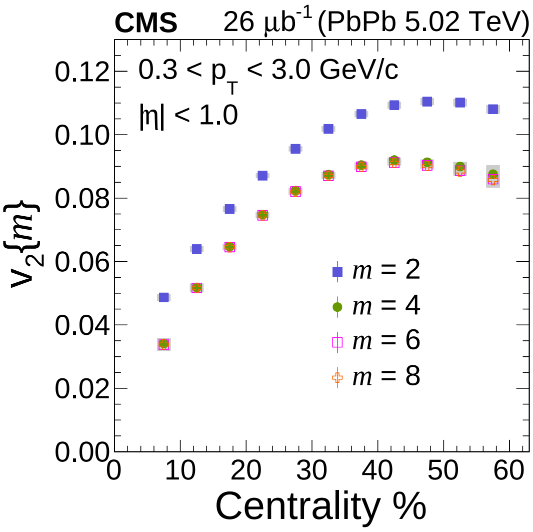

Figure 2: Elliptic-flow cumulant harmonics with values obtained from the moments of the unfolded $p(v_2)$ distributions. Statistical uncertainties are smaller than the symbol size. Systematic uncertainties are shown as gray bands.

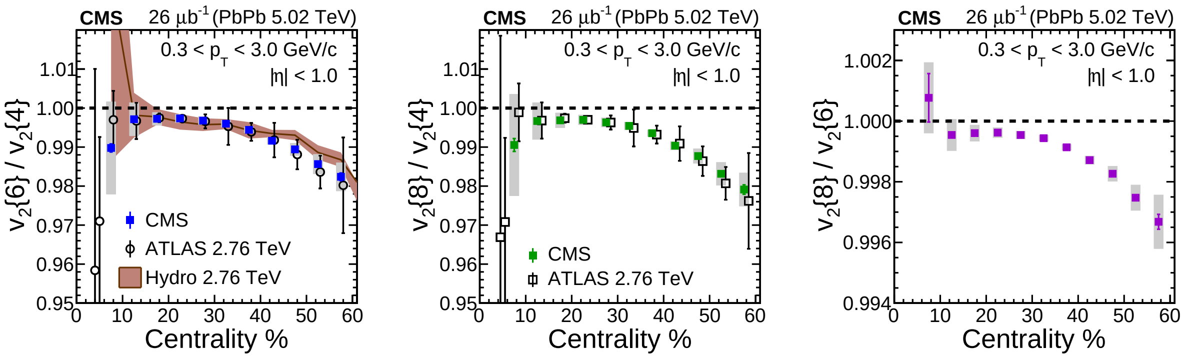

Figure 3: Ratios of higher order cumulant elliptic-flow harmonics with values obtained from the moments of the unfolded $p(v_2)$ distributions. Both statistical (lines) and systematic (gray bands) uncertainties are shown. Hydrodynamic predictions for 2.76 TeV collisions from Ref. [27] are presented as a dark color band and are compared to the measured $v_2\{6\}/v_2\{4\}$ ratio. In addition, higher order cumulant ratios reported by the ATLAS Collaboration for 2.76 TeV collisions [14] with $0.5 < p_T < 20.0\,\mathrm{GeV}/c$ and $|\eta| < 2.5$ are compared to the 5.02 TeV measurement. The error bars on the ATLAS measurement represent the quadratic sum of statistical and systematic uncertainties and points are offset horizontally for clarity.

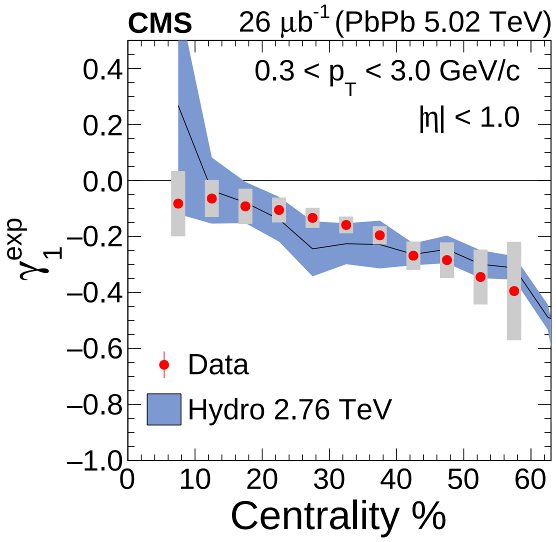

Figure 4: The skewness estimate with respect to the reaction plane determined using the elliptic-flow harmonic based on different cumulant orders. Both statistical and systematic uncertainties are shown, where statistical uncertainties are smaller than the data points. Hydrodynamic model predictions for 2.76 TeV PbPb collisions from Ref. [27] are shown as a colored band.

Both elliptic power and Bessel–Gaussian parametrizations used for fits such as shown in Fig. 1 assume a linear response between eccentricity and flow, but only the elliptic power law allows for a finite skewness. This flexibility results in the elliptic power function being in better agreement with the observed fluctuation behavior than the Bessel–Gaussian parametrization, yielding χ^2/dof goodness of fit values on the order of unity. Point-by-point systematic uncertainties on the unfolded distributions are correlated and are thus not considered in the fits. The fit parameters for the elliptic power function are shown in Fig. 5 for the different centrality bins. Here, fits do not converge for central collisions and parameters are shown for centralities greater than ≈15%. Viscous hydrodynamics calculations indicate that deviations from thermal equilibrium will result in a reduced correspondence between the initial-state geometry and the flow signal in peripheral collisions [21, 22], which is consistent with the data.

Theoretical predictions at 2.76 TeV from Ref. [11] are compared to the current analysis in Fig. 5. A viscous hydrodynamic calculation with Glauber initial conditions and an η/s value of 0.19 is in agreement with the experimental k_2 values. Predictions obtained using Glauber and IP-Glasma [41, 42] initial conditions, where the IP-Glasma model includes gluon saturation effects, are shown for the ε_0 and α parameters. These latter two calculations qualitatively capture the observed behavior for the α-parameter, but a significant difference is found in comparing the theoretical ε_0 values with experiment. This difference might reflect a nonlinear response term, which will alter the magnitude of the flow response coefficient and consequently the ε_0 and α parameters, as suggested in Ref. [11].

7 Summary

In summary, a non-Gaussian behavior is observed in the event-by-event fluctuations of the elliptic flow v_2 coefficients in PbPb collisions recorded by the CMS detector at $\sqrt{s_{NN}} = 5.02$ TeV. The probability distributions $p(v_2)$ for 5%-centrality bins between 5% and 60% centrality are

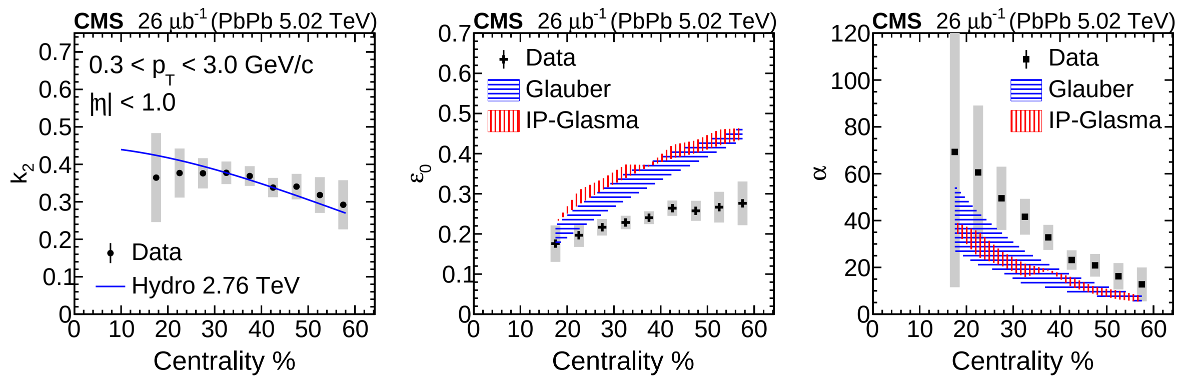

Figure 5: Centrality dependence of the parameters extracted from elliptic power function fits to the unfolded $p(v_2)$ distributions. Both statistical (error bars) and systematic (shaded boxes) uncertainties are shown. The solid lines represent theoretical calculations from Ref. [11] using viscous hydrodynamics with Glauber initial conditions and an η/s value of 0.19 to determine the response coefficient k_2. Glauber (blue shaded band) and IP-Glasma (red shaded band) model calculations from Ref. [11] are shown for the α and ε_0 parameters.

found by unfolding statistical resolution effects from measured flow distributions. The v_2 coefficients corresponding to different cumulant orders are calculated from the moments of the unfolded $p(v_2)$ distributions. A rank ordering of $v_2\{4\} > v_2\{6\} > v_2\{8\}$, with differences on the order of a few percent, is observed for noncentral events with centralities greater than ≈15%. The standardized skewness of each $p(v_2)$ distribution is calculated using the cumulant results. In cases where there is a splitting of the cumulant values, the standardized skewness is found to be negative with an increasing magnitude as collisions become less central. Bessel–Gaussian and elliptic power functions are fitted to the unfolded $p(v_2)$ distributions. The two distributions are similar for central collisions, though the elliptic power function provides a better description for noncentral collisions.

Based on the elliptic power function fits, the centrality dependence of the flow response coefficient, which relates the final state geometry to the initial state energy density distribution, is found to be consistent with model calculations. However, the observed eccentricities are smaller than predictions based on either the Glauber model or the IP-Glasma model initial conditions with an assumed linear flow response. The current results illustrate that LHC experiments now have the precision to explore the details of the initial-state fluctuation behavior.

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