Probing Charm Quark Dynamics via Multiparticle Correlations in Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

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Multiparticle azimuthal correlations of prompt D^0 mesons are measured in Pb-Pb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. For the first time, a four-particle cumulant method is used to extract the second Fourier coefficient of the azimuthal distribution (v_2) of D^0 mesons as a function of event centrality and the D^0 transverse momentum. The ratios of the four-particle v_2 values to previously measured two-particle cumulant results provide direct experimental access to event-by-event fluctuations of charm quark azimuthal anisotropies. These ratios are also found to be comparable to those of inclusive charged particles in the event. However, hints of deviations are seen in the most central and peripheral collisions. To investigate the origin of flow fluctuations in the charm sector, these measurements are compared to a model implementing fluctuations of charm quark energy loss via collisional or radiative processes in the quark-gluon plasma. These models cannot quantitatively describe the data over the full transverse momentum and centrality ranges, although the calculations with collisional energy loss provide a better description of the data.

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A strongly coupled quark-gluon plasma (QGP) has been studied in nucleus-nucleus collisions at the BNL RHIC [1–4] and CERN LHC [5,6]. This medium exhibits the behavior of a nearly perfect liquid [7,8]. The azimuthal anisotropy of produced hadrons, resulting from pressure-driven expansion, is a powerful tool to study QGP dynamics and can be characterized by the Fourier coefficients (v_n) of the hadrons' azimuthal angle (ϕ) distribution [9]. The second-order Fourier coefficient (v_2), known as elliptic flow, of low transverse momentum (P_T) particles reflects the QGP response to the average initial collision geometry and its event-by-event fluctuations [9]. The v_2 coefficient is also influenced by the path length dependence of parton energy loss at high P_T [10–12].

Charm and beauty (heavy-flavor) quarks are produced in the initial stages of a collision via hard scattering processes [13]. At the LHC, a significant elliptic flow is observed for mesons containing a charm quark, namely prompt D^0 [14–18] and J/ψ [19–21], and for leptons from heavy-flavor hadron decays [22,23]. However, the first measurements with mesons containing unambiguous beauty quarks, specifically the $\Upsilon(1S)$ and $\Upsilon(2S)$ [24,25], show v_2 values compatible with zero. The D^0 meson v_2 has been measured using a two-particle cumulant method, $v_2\{2\}$ [26], at RHIC [27,28] and LHC [14–18]. This method correlates a D^0 meson with each charged particle in the event. The results indicate that low-P_T charm quarks are strongly coupled to the QGP, as reproduced by hydrodynamic models [8].

The magnitude of event-by-event fluctuations [29] of azimuthal anisotropy harmonics from heavy-flavor quarks has not been experimentally measured. Multiparticle correlation techniques involving four or more particles, $v_2\{n\}$, with $n \geq 4$ [30], allow direct access to cumulants of the v_2 probability density distribution. The technique has been widely applied in the light-flavor sector to extract the magnitude of v_2 fluctuations, which is then used to constrain fluctuations of the initial-state geometry. It has been recently proposed that for hard probes (such as high-P_T jets, and heavy-flavor hadrons), fluctuations of anisotropy harmonics are not only influenced by the initial-state geometry, but are also sensitive to final-state fluctuations of energy loss when these hard probes propagate in the QGP medium [31]. Therefore, measurements of $v_2\{4\}$ and its ratio to $v_2\{2\}$ for heavy-flavor hadrons have the potential to set constraints on the mechanism of heavy-quark energy loss, especially how it fluctuates on an event-by-event basis in QGP.

In this Letter, the prompt D^0 meson v_2 coefficient is measured for the first time using four-particle correlations, and the ratio $v_2\{4\}/v_2\{2\}$ is presented. These measurements use data from lead-lead (Pb-Pb) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, collected by the CMS detector at the LHC in 2018. The behavior of v_2 is examined in the rapidity (y) range $|y| < 1$

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over the P_T range of 2–15 GeV, and in the event centrality classes (i.e., the percentage ranges of the total inelastic hadronic cross section) of 10%–30% and 30%–50%. A 0% centrality corresponds to the largest overlap of the two nuclei. The centrality dependence of v_2 is also measured over the broader range of 5%–60% for $2 < P_T < 8$ GeV. Tabulated results are provided in the HEPData record for this analysis [32].

The CMS apparatus [33] is a multipurpose, nearly hermetic detector, designed to trigger on [34,35] and identify electrons, muons, photons, and hadrons [36–39]. In this analysis, the information from two subdetectors were used: the silicon inner tracker, which measures charged particles within the range of pseudorapidity $|\eta| < 3.0$; and the hadronic forward (HF) calorimeters, made of steel and quartz fibers, which extend the pseudorapidity coverage provided by the barrel and end-cap detectors to about $|\eta| < 5.0$, and are segmented to form 0.175×0.175 $(\Delta\eta \times \Delta\phi)$ towers.

The data analyzed consist of 4.27×10^9 minimum bias events, corresponding to an integrated luminosity of $0.58\ \mathrm{nb}^{-1}$. The events are triggered by requiring signals above thresholds in the range of ~6–12 GeV in both sides of the HF calorimeters [35]. Events must also have at least one reconstructed primary vertex within 15 cm of the interaction point along the beam axis. The primary vertex is selected as the one with the highest track multiplicity in the event. The effects from concurrent interactions in the same bunch crossing were shown to be negligible. The centrality is calculated using the HF calorimeters [40].

Monte Carlo (MC) event samples are simulated containing either prompt or nonprompt D^0 mesons; the latter originate from beauty hadron decays. The simulated events are generated using PYTHIA8.212 [41], tune CP5 [42], and embedded into MC Pb-Pb events from HYDJET 1.9 [43]. The prompt D^0 meson event sample is employed to define signal selections and efficiency corrections, while the other sample is used to estimate systematic uncertainties from nonprompt D^0 contamination.

Both D^0 and $\bar{D}^0$ mesons are reconstructed via the process $D^0 \to \pi^+ + K^-$ $(\bar{D}^0 \to \pi^- + K^+)$, with a branching fraction of $(3.95 \pm 0.03)\%$ [44]. This is accomplished by combining pairs of oppositely charged tracks having an invariant mass (m_{inv}) within ± 200 MeV of the world-average D^0 mass of 1865 MeV [44]. Tracks are required to have $P_T > 1.0$ GeV and $|\eta| < 2.4$ and must satisfy high-purity quality criteria [39]. Two D^0 candidates for each pair of selected tracks are considered by assuming one track has the pion mass, while the other has the kaon mass, and vice versa. Kinematic fits [45] are performed to reconstruct the decay (secondary) vertex of each D^0 candidate. A boosted decision tree (BDT) algorithm, as implemented in the TMVA software package [46], maximizes the statistical significance of prompt D^0 meson signals. Particle pairs having the same charge, and again assumed to be a pion and kaon, are used as the background distribution for training the BDT. This analysis uses the same BDT parameters as Ref. [18].

This analysis shares the same datasets and uses a similar procedure to that described in Ref. [18], in which the D^0 meson v_2 is measured using the two-particle correlation (or cumulant) method, $v_2\{2\}(D^0)$, where the D^0 meson v_2 signal is extracted by correlating a D^0 meson with reference particles measured in the HF detectors. To measure the differential second-order (elliptic) harmonic from the four-particle cumulant, $v_2\{4\}(D^0)$ [30], a first step involves either two- or four-particle correlations calculated using energy deposits in the HF towers to obtain elliptic harmonics of reference particles. Here, each HF tower is used to represent one or more particles with a weight applied corresponding to its deposited transverse energy in the calculation of cumulants when averaging over all HF towers, as detailed below. The two- and four-particle azimuthal correlations for the nth harmonic are defined as

$$\langle\langle 2\rangle\rangle = \langle\langle e^{in(\phi_1^a - \phi_2^b)}\rangle\rangle, \qquad \langle\langle 4\rangle\rangle = \langle\langle e^{in(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^b)}\rangle\rangle. \quad (1)$$

Here, ϕ_{j} $(\mathrm{j} = 1, \ldots, 4)$ are the azimuthal angles of one unique combination of multiple particles in an event and the double average symbol $\langle\langle \cdots \rangle\rangle$ indicates that the average is taken over all unique particle combinations and for all events. In addition, the superscripts a and b indicate towers chosen from two different HF calorimeters, HF− $(-5 < \eta < -3)$ or HF+ $(3 < \eta < 5)$. In a second step, the four-particle cumulant of reference particle azimuthal correlations, $c_n\{4\}$, is calculated as [30,47–49]

$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2. \quad (2)$$

To measure the prompt D^0 meson v_2 coefficient, the ϕ_1^a from an HF tower in Eq. (1) is replaced with a D^0 candidate's azimuthal angle selected within the tracker acceptance $|\eta| < 2.4$. To suppress the nonflow effects from sources such as resonance decays or jets, in the two-particle cumulant method, a tower with ϕ_2 is selected from the HF calorimeter (HF+ or HF−) having the opposite η sign as that of the D^0 candidate. For the four-particle correlations method, ϕ_2^a is picked from the HF detector having the same η sign as the D^0 candidate, but ϕ_3^b and ϕ_4^b are chosen from the other HF detector. Studies performed with simulated events indicate that nonflow effects are negligible when measuring $v_2\{2\}$ with these η gaps [48,50]. These modified particle correlators involving a D^0 meson are denoted by $\langle\langle 2'\rangle\rangle$ and $\langle\langle 4'\rangle\rangle$. The differential four-particle cumulant of D^0 mesons is then defined as [30,49]

$$d_n\{4\} = \langle\langle 4'\rangle\rangle - 2\langle\langle 2'\rangle\rangle\langle\langle 2\rangle\rangle. \quad (3)$$

Finally, with respect to the reference four-particle cumulants, the differential four-particle $v_n(D^0)$ coefficients are extracted as in Refs. [30,49],

$$v_n\{4\}(D^0) = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}, \qquad (4)$$

which includes contributions of both true signal and background D^0 candidates. To separate the v_2 signal of D^0 mesons ($v_2^{\mathrm{sig}}\{4\}$) from background candidates ($v_2^{\mathrm{bkg}}\{4\}$), the same two-step fitting procedure as in Ref. [18] is performed. First, the invariant mass spectrum of all D^0 candidates is fit using a formula containing five components: (i) A sum of two Gaussian functions having the same mean but different widths is used for the D^0 signal; (ii) a single Gaussian function describes the invariant mass spectrum of D^0 candidates with an incorrect mass assignment resulting from the exchange of the kaon and pion designations; (iii) a Crystal Ball function [51] is used for the processes $D^0 \to K^+K^-$ [52]; (iv) another Crystal Ball function is used to describe $D^0 \to \pi^+\pi^-$ [52]; (v) a third-order polynomial is used to model the combinatorial background. The first four components are initialized by values calculated using simulated events, and their widths are allowed to vary with a common scale factor during the fit to data. Using the signal and background D^0 candidate yield fraction extracted from the invariant mass fit, the measured v_2 data of all D^0 candidates, $v_2^{\mathrm{sig+bkg}}\{4\}$ can then be decomposed into the v_2 values of signal and background D^0 candidates, by fitting to a linear combination of the two components. An example of the full fitting procedure is shown in Fig. 1. The influence from the D^0 meson v_2 signal can be clearly seen in the lower panel as a dip in the $v_2^{\mathrm{sig+bkg}}\{4\}$ distribution.

Statistical uncertainties are evaluated from data with the method described in Refs. [48,53]. The data are divided into 20 equal subsets, and the standard deviation of the resulting cumulant distribution is used to estimate the statistical uncertainty.

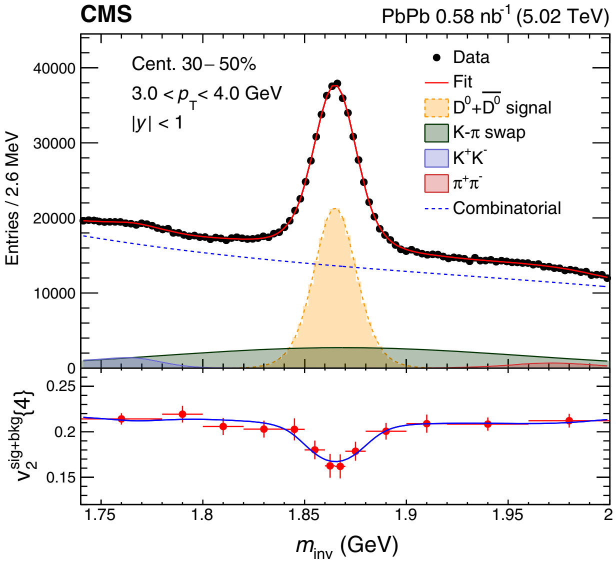

FIG. 1. An example of the two-step fit of the mass spectrum (upper) and $v_2^{\mathrm{sig+bkg}}\{4\}$ (lower) in the P_T interval 3–4 GeV for the centrality class 30%–50%.

The sources of systematic uncertainties include the D^0 meson BDT selection (i.e., the choice of the working point), the background invariant mass probability distribution (PD), the PD of the v_2 background, the detector acceptance and D^0 meson reconstruction efficiency correction of the D^0 meson yield, as well as nonprompt D^0 meson contamination. The uncertainties in the $v_2\{4\}/v_2\{2\}$ ratios account for the correlations between uncertainty sources for $v_2\{4\}$ and $v_2\{2\}$. The systematic uncertainty of the BDT selection is assigned by varying up and down the BDT discriminant requirement. The magnitudes of these variations depend on the collision centrality and are derived by comparing the BDT discriminant requirement optimization in simulation and in a subset of data events. It is 0.002–0.004 for $v_2\{4\}$ and 0.020–0.035 for $v_2\{4\}/v_2\{2\}$. The systematic uncertainties from the mass background PD are evaluated by changing the default third-order polynomial function to a second-order polynomial or exponential function, and are between 0.002–0.005 for $v_2\{4\}$ and 0.004–0.019 for $v_2\{4\}/v_2\{2\}$. The systematic uncertainties from the v_2 background PD are evaluated by changing the default linear function to a second-order polynomial or a constant function, and are 0.002–0.005 for $v_2\{4\}$ and 0.003–0.014 for $v_2\{4\}/v_2\{2\}$. Although the efficiency of selecting D^0 mesons essentially cancels when measuring the v_2, the systematic uncertainty from the efficiency correction is evaluated by comparing results with and without applying efficiency corrections to the D^0 meson yield. The D^0 yield corrections are applied in intervals of P_T for $|y| < 1$, using the acceptance and efficiency values obtained from simulated events. This correction yields the uncertainties of 0.004–0.016 for $v_2\{4\}$ and 0.033–0.116 for $v_2\{4\}/v_2\{2\}$ for the $2 < P_T < 3$ GeV bin (with the ranges corresponding to the variation between the centrality bins of 10%-30% and 30%–50%), and becomes negligible at higher P_T values. The uncertainties from efficiency correction are also quoted in the P_T-integrated ($2 < P_T < 8$ GeV) v_2 results in different centralities in the range of 5%–60%, with an average value of 0.006 for $v_2\{4\}$ and of 0.015 for $v_2\{4\}/v_2\{2\}$. The systematic uncertainties from the nonprompt D^0 contamination (2%–5%) are evaluated by using the relative uncertainty estimated in Ref. [18] for $v_2\{2\}$, and are 0.001–0.005 for $v_2\{4\}$. All the different sources are added together in quadrature and the total uncertainty is 0.008–0.018 for $v_2\{4\}$ and 0.021–0.121 for $v_2\{4\}/v_2\{2\}$.

Figure 2 shows $v_2\{4\}$ results of prompt D^0 mesons (upper panel) within the midrapidity range $|y| < 1$ as a function of P_T. These v_2 values are measured in the centrality classes 10%–30% and 30%–50%. The $v_2\{2\}$ values, measured previously by CMS in Ref. [18], are also shown for comparison. As previously observed for $v_2\{2\}$,

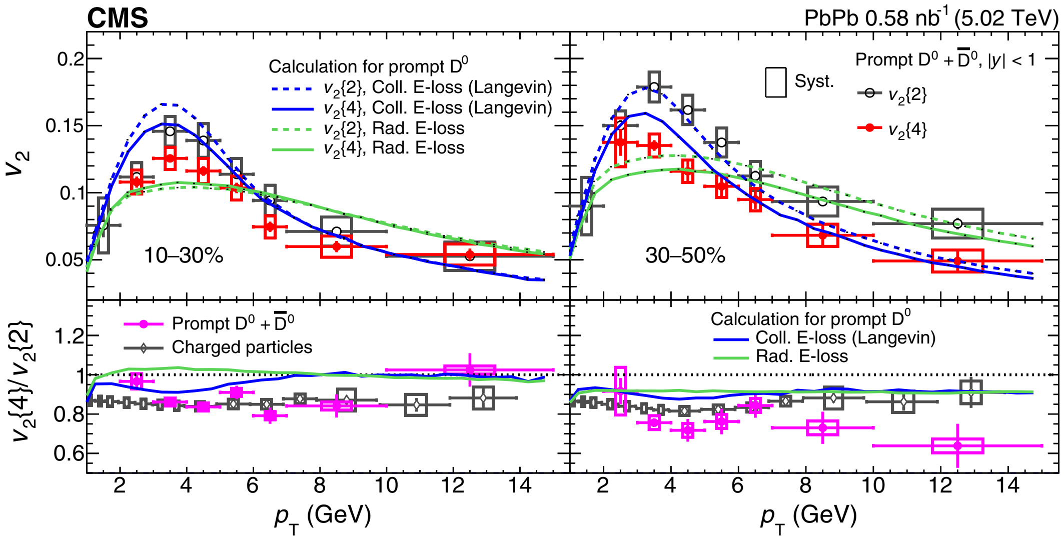

FIG. 2. Upper panel: prompt D^0 meson $v_2\{2\}$ and $v_2\{4\}$ coefficients as a function of P_T, for the centrality classes 10%–30% (left) and 30%–50% (right). The lines indicate calculations from the DABMod model [11,12], with solid (dashed) lines indicating $v_2\{4\}$ ($v_2\{2\}$) values. Blue lines include Langevin dynamics and green lines include radiative energy loss (E-loss). Lower panel: the prompt D^0 meson $v_2\{4\}/v_2\{2\}$ ratios are shown and compared to those for charged particles in the pseudorapidity range $|\eta| < 1$ [53]. The vertical bars represent statistical uncertainties and the open boxes denote the systematic uncertainties.

the measured $v_2\{4\}$ values rise with increasing P_T, up to a maximum near $P_T \approx 3.5$ GeV, and then diminish. The $v_2\{4\}$ values are below the $v_2\{2\}$ measurements, with the difference being more pronounced above 3 GeV and for the 30%–50% centrality range. A similar observation has been found for all charged particles in the event [53], which is predicted by initial-state geometry fluctuations modeled by using Bessel-Gaussian and elliptic power eccentricity distributions [29,54]. The elliptic power distribution is a two-parameter distribution, where one of the parameters corresponds to the intrinsic eccentricity, while the other parameter controls the magnitude of eccentricity fluctuations. Theoretical calculations for prompt D^0 meson v_2 based on a state-of-the-art D and B meson modular simulation code (called DABMod [11,12]) with the option of turning on energy loss by gluon radiation or alternatively by elastic collisions described by Langevin dynamics during the heavy-quark propagation, are also shown in the upper panel of Fig. 2. The radiative energy loss process is expected to be the dominant phenomenon in the high-P_T region. Langevin dynamics, which describe the propagation of heavy quarks in the medium as a Brownian motion, can account for collisional processes using Langevin-like equations [11] in the low- and intermediate-P_T regions. Both models seem to capture the general trends of the data, without reproducing them quantitatively.

To further investigate the underlying physics processes behind elliptic flow fluctuations of charm quarks, the ratios $v_2\{4\}/v_2\{2\}$ are presented as a function of P_T, up to 15 GeV, in the lower panel of Fig. 2. Generally speaking, a larger deviation of $v_2\{4\}/v_2\{2\}$ ratios from unity indicates a larger magnitude of flow fluctuations. The same ratios for charged particles (dominated by light-flavor hadrons) are shown. The ratios for prompt D^0 mesons are consistent with those for charged particles. The roughly flat behavior of the ratios at low P_T suggests that initial-state geometry fluctuations are likely the dominant source of flow fluctuations there [11]. The ratios based on the DABMod model for D^0 mesons [11,12], also shown in Fig. 2 (bottom), lie systematically above the data, suggesting an underestimation of the magnitude of flow fluctuations in the data.

The P_T-integrated results of $v_2\{4\}$ for $2 < P_T < 8$ GeV and $|y| < 1$ are shown as a function of centrality from 5% to 60% in Fig. 3. The $v_2\{2\}$ values measured previously by CMS in Ref. [18] are plotted for comparison. The $v_2\{4\}/v_2\{2\}$ ratios are shown in the lower panel of Fig. 3. The prompt D^0 data are also compared to those of inclusive charged particles within the range $|\eta| < 1$ and $2 < P_T < 8$ GeV.

Similar to the D^0 meson $v_2\{2\}$ coefficient, the D^0 meson $v_2\{4\}$ value increases with centrality in the 5%–40% range, and then decreases for more peripheral collisions. This trend is qualitatively reproduced by calculations incorporating an interplay of initial-state geometry and parton energy loss in QGP. Within the 10%–40% centrality range, the $v_2\{4\}/v_2\{2\}$ ratios are almost identical between prompt D^0 mesons and inclusive charged particles within uncertainties. This indicates that, within this centrality range, the dominant source of flow fluctuations for heavy flavor is similar to that for soft light-flavor particles, namely initial-state geometry fluctuations, and therefore the contribution from final-state fluctuations is small. The hint of different trends in $v_2\{4\}/v_2\{2\}$ between D^0 mesons and charged particles seen in the most central and most

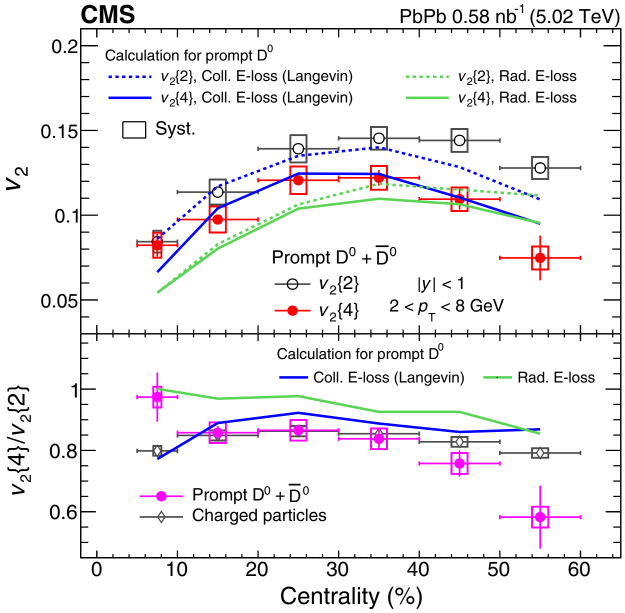

FIG. 3. Upper panel: the prompt D^0 meson $v_2\{2\}$ and $v_2\{4\}$ as a function of centrality. The lines indicate calculations from the DABMod model [11,12], with solid (dashed) lines indicating $v_2\{4\}$ ($v_2\{2\}$) values. Blue lines include Langevin dynamics and green lines include radiative energy loss (E-loss). Lower panel: the prompt D^0 meson $v_2\{4\}/v_2\{2\}$ are compared to the same ratio for charged particles in the pseudorapidity range $|\eta| < 1$ [53]. The vertical bars represent statistical uncertainties and open boxes denote the systematic uncertainties.

peripheral events could indicate that fluctuations from final-state effects, such as parton energy loss, in hard processes become visible for charm mesons [11]. For example, as the system size becomes smaller for peripheral events, the number of scatterings a hard probe experiences with QGP will decrease, leading to larger fluctuations in the energy loss on an event-by-event basis. However, the experimental uncertainties are still large, with the difference of ~2 standard deviations between the values. Calculations based on the DABMod model [11,12] assuming collisional (or Langevin dynamics) and radiative energy loss processes are also shown in Fig. 3. A better description of the experimental data is obtained using the Langevin dynamics, although no increase or decrease for the most central or peripheral events, respectively, is predicted.

In summary, the first measurements of the elliptic flow for prompt D^0 and $\bar{D}^0$ mesons using a four-particle cumulant method are presented. These $v_2\{4\}$ values are systematically lower than the measured two-particle elliptic flow values, $v_2\{2\}$, indicating the presence of event-by-event fluctuations in the flow signal [29]. To further investigate the origin of v_2 fluctuations, $v_2\{4\}/v_2\{2\}$ ratios of prompt D^0 mesons are compared to those of light-flavor hadrons. Similar trends for both charm mesons and light-flavor hadrons are observed, suggesting that the dominant contribution to v_2 fluctuations comes from the initial geometry. An indication of splitting of the $v_2\{4\}/v_2\{2\}$ ratios between charm mesons and light-flavor hadrons in the most central and most peripheral events is seen, which may suggest an additional contribution, such as energy loss fluctuations. Model calculations implementing collisional energy loss mechanisms provide a better description of the data than those considering radiative energy loss.

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