Measurements of azimuthal anisotropy of nonprompt \( D^0 \) mesons in PbPb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV

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Abstract

Measurements of the elliptic \( (v_2) \) and triangular \( (v_3) \) azimuthal anisotropy coefficients are presented for \( D^0 \) mesons produced in \( b \) hadron decays (nonprompt \( D^0 \) mesons) in lead-lead collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV. The results are compared with previously published charm meson anisotropies measured using prompt \( D^0 \) mesons. The data were collected with the CMS detector in 2018 with an integrated luminosity of 0.58 nb\(^{-1}\). Azimuthal anisotropy is sensitive to the interactions of quarks with the hot and dense medium created in heavy ion collisions. Comparing results for prompt and nonprompt \( D^0 \) mesons can assist in understanding the mass dependence of these interactions. The nonprompt results show lower magnitudes of \( v_2 \) and \( v_3 \) and weaker dependences on the meson transverse momentum and collision centrality than those found for prompt \( D^0 \) mesons. By comparing to theoretical predictions, the results imply that there is a mass hierarchy of quark interactions with the medium.

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1 Introduction

In ultra-relativistic heavy ion collisions, cold nuclear matter transforms into a state of strongly coupled matter, called the quark-gluon plasma (QGP) [1–4]. One of the main features of the QGP is the collective motion of its constituents. This collectivity can be quantified by measuring the momentum anisotropy of the particles that emerge from the collision. In the plane perpendicular to the beam axis (transverse plane), this anisotropy results from the initial transverse spatial anisotropy of the colliding system. To quantify this effect, azimuthal (Fourier) coefficients of order $n$, $v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$ can be used, where $\phi$ is the single-particle azimuthal angle and $\Psi_n$ is the first angle where the $n$-th harmonic component has its maximum multiplicity [5, 6]. The measured $v_n$ values for low-momentum light hadrons can be described by relativistic hydrodynamics, and this behavior is known as collective anisotropic flow [7–9].

The second Fourier coefficient, $v_2$ (referred to as elliptic flow), arises from the combined effects of the elongated shape and the event-by-event fluctuations of the overlap region of the colliding nuclei [10]. The third coefficient, $v_3$ (referred to as triangular flow), is predominantly due to the fluctuations.

Because of their large mass, bottom (b) and charm (c) quarks are produced at the earliest stage of the collision [11], but their azimuthal distributions can be affected by their interaction with the medium as they travel through the QGP [12]. At low transverse momentum ($p_T$), it is believed that heavy quarks thermalize and, therefore, they should follow the motion of the light flavor particles [13]. In the high $p_T$ region, the flow could be caused by the path length dependence of parton energy loss [14, 15]. Hence, studying the collectivity of heavy quarks in heavy ion collisions can provide important inputs for understanding the properties of the QGP. Significant $v_2$ and $v_3$ coefficients of charm hadrons in lead-lead (PbPb) collisions have already been measured at the CERN LHC, proving that heavy quarks exhibit collective flow [16–21]. An early measurement by the CMS Collaboration of the elliptic flow of $J/\psi$ from b hadron decays was consistent with zero, albeit with large uncertainties [22]. Recently, the ALICE Collaboration measured the $v_2$ of electrons from b hadron decays [23], and the ATLAS Collaboration measured both $v_2$ and $v_3$ of muons from b hadron decays [19]. These results show a nonzero elliptic flow for b hadrons, as well as clear mass ordering, with smaller measured values of Fourier coefficients than those found for lighter quarks. With respect to these $J/\psi$ or lepton measurements, the $b \rightarrow D^0$ channel is a promising laboratory because of its lower $p_T$ coverage and large branching ratio ($\sim 70\%$). In addition, because of its large mass, the $D^0$ momentum is more closely correlated with the b quark momentum than is the case for leptons.

In this Letter, the first $v_2$ and $v_3$ measurements of $D^0$ mesons from b hadron decay (nonprompt $D^0$ mesons) in large collision systems are reported, using PbPb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. Results for $D^0$ mesons in the rapidity range $|y| < 1$ are shown as a function of their $p_T$, spanning 1–30 GeV/c, and in three classes of PbPb centrality: 0–10%, 10–30%, and 30–50%. These centrality percentages represent the fraction of the total inelastic hadronic cross section, with 0% corresponding to full overlap of the two colliding nuclei. The broad range in $p_T$ enables a comprehensive study of different flow generation mechanisms. The results are compared with azimuthal anisotropy measurements of $D^0$ mesons that do not come from b hadron decays (prompt $D^0$ mesons) [18], as well as with theoretical predictions. Tabulated results are provided in the HEPData record for this analysis [24].
2 Experimental setup and data sample

The CMS apparatus \cite{25} is a multipurpose, nearly hermetic detector, designed to trigger on \cite{26,27} and identify electrons, muons, photons, and (charged and neutral) hadrons \cite{28–30}. A global algorithm \cite{31} aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the pseudorapidity range \(3.0 < |\eta| < 5.2\).

The HF calorimeters are subdivided into “towers” with \(\Delta\eta \times \Delta\phi = 0.175 \times 0.175\), and energy deposited in a tower is treated as a detected hadron in this analysis. They serve as luminosity monitors and the total energy deposited in both HF calorimeters is used for centrality determination \cite{32}. Events are filtered using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors \cite{26}. The second level, known as the high-level trigger \cite{27}, consists of a farm of processors running a version of the full event reconstruction software.

The data analyzed in this Letter consist of minimum bias (MB) PbPb events corresponding to an integrated luminosity of 0.58 nb\(^{-1}\) \cite{33,34}. The MB selection requires signals above readout thresholds in the range of \(\sim 6–12\) GeV on both sides of the HF calorimeters \cite{27}. The events are further filtered to remove background events (beam-gas interactions and nonhadronic collisions) by applying the procedure described in Ref. \cite{35}. The final results include only events with at least one vertex associated with two or more tracks (primary vertex) within 15 cm from the nominal interaction point along the beam direction, and at least two towers with energy larger or equal to 4 GeV in each of the HF detectors. Finally, in order to suppress the contamination from events with multiple ion collisions, the shapes of the clusters in the pixel part of the inner tracker are required to be compatible with those expected in single PbPb collisions.

Simulated events from Monte Carlo (MC) generators are used to study the kinematics of \(D^0\) mesons in PbPb collisions. The \(D^0\) mesons are generated with PYTHIA 8.212 \cite{36}, tune CP5 \cite{37}, while their decays are modeled with EVTGEN 1.3 \cite{38}. Both prompt and nonprompt \(D^0\) samples are produced. The decay products of the \(D^0\) mesons are then embedded into MB events generated using HYDJET 1.9 \cite{39}. The response of the CMS detector to these combined events is simulated with GEANT4 \cite{40}.

3 Analysis procedure

Inclusive (both prompt and nonprompt) \(D^0\) and \(\bar{D}^0\) meson candidates are reconstructed via their decay channels: \(D^0 \rightarrow \pi^+ + K^-\) and \(\bar{D}^0 \rightarrow \pi^- + K^+\). Both \(D^0\) and \(\bar{D}^0\) are referred to as \(D^0\) in this Letter. All tracks used in the analysis have \(p_T > 1\) GeV/c and \(|\eta| < 1.2\). To ensure the best track quality, only tracks that satisfy high purity \cite{30} criteria are considered. In addition, the relative uncertainty in the track \(p_T\) measurement is required to be less than 10\%. The number of hits along the track trajectory in the tracker must be greater or equal to 11. The \(\chi^2\) of the track fit divided by the total number of degrees of freedom of the fit, and also divided by the total number of tracker layers having a hit along the track path, must be less than 0.18. Candidates are formed by combining pairs of tracks from oppositely-charged particles and requiring an invariant mass \((m_{\text{inv}})\) within a \(\pm 200\) MeV/c\(^2\) window of the world-average \(D^0\) meson mass of 1865 MeV/c\(^2\) \cite{41}. Since no particle identification is available, both
Further selection is done by applying a boosted decision tree (BDT) algorithm implemented using the TMVA package [42]. For the BDT training, the signal candidates are taken from the simulated events in which reconstructed D⁰ mesons are required to match the generated nonprompt D⁰ particles. The background training sample consists of two components combined together: combinatorial background and prompt D⁰ production. The combinatorial background sample is composed of D⁰ candidates reconstructed from data whose mass is three to six standard deviations away from the nominal D⁰ meson mass (\sim 1.795–1.830 and \sim 1.900–1.935 GeV/c²). The prompt D⁰ meson component of the background sample consists of D⁰ candidates that correspond to simulated prompt D⁰ mesons in the MC events. In this way, the training is optimized to favor the D⁰ mesons produced in b hadron decays. Training is performed separately for each p_T range and centrality class. The variables related to D⁰ mesons used to discriminate the signal from the background are: \chi² probability for the D⁰ vertex fit, the distance between the D⁰ and primary vertices and its significance, as well as the angle between the momentum of the D⁰ meson candidate and the line connecting the primary and D⁰ vertices (pointing angle). In addition, related to the decay products of the D⁰ meson candidate, the variables used are: the significance of the distances of closest approach (DCA) to the primary vertex (both along and perpendicular to the beam direction), and the number of hits assigned to a particular track. These variables are chosen by analyzing their importance in the decision tree and the correlation matrix among all variables. The BDT cut is optimized to correspond to the maximal correlation matrix among all variables. The BDT cut is optimized to correspond to the maximal correlation matrix among all variables. The BDT cut is optimized to correspond to the maximal correlation matrix among all variables. Therefore, before performing this calculation, the p_T spectrum of D⁰ mesons in the simulation is weighted to match that in the data.

The measurement of inclusive D⁰ meson v_n coefficients employs the scalar-product (SP) method [43] used in previous CMS publications for prompt D⁰ mesons [17, 18].

In this method, the v_n coefficients of all D⁰ candidates (v_{n sig+bkg}) are determined using

\[ v_n\{SP\} = \frac{\langle Q_n^{D^0} Q_A^{B} \rangle}{\sqrt{\langle Q_{nA} Q_{nB}^{*} \rangle \langle Q_{nA} Q_{nC}^{*} \rangle}} \] (1)

where the Q-vectors are defined as \( Q_n = \sum_{j=1}^{w_j} e^{i\phi_j} w_j \), the asterisk symbol (*) means complex conjugation, and the subscripts A, B, and C refer to different subevents. In each event, the sum for \( Q_{nA} \) and \( Q_{nB} \) is over all hadrons detected in HF which are above a threshold energy, while the sum for \( Q_{nC} \) includes all reconstructed tracks above a \( p_T \) threshold. The \( Q_n^{D^0} \) signifies the flow vector of a D⁰ meson candidate within a particular kinematic range. The weight \( w_j \) is a dimensionless quantity and corresponds to the energy deposited in the HF tower in GeV, or to the track \( p_T \) in GeV/c, at azimuthal angle \( \phi_j \), or \( w_j = 1 \) in the case of D⁰ meson candidates. The subevent A (B) uses the negative (positive) side of the HF when the D⁰ meson candidate is at positive pseudorapidity, and vice versa. This choice of subevents avoids autocorrelations and results in an \( \eta \) gap of at least three units between the D⁰ meson daughters and particles from the underlying subevent, thereby suppressing short-range correlations. Flattening and recentering
procedures are applied to the $Q$-vectors related to HF and the tracker, for removing detector acceptance effects [44, 45]. The averages $\langle Q_n A Q_{nB} \rangle$, $\langle Q_n A Q_{nC} \rangle$, and $\langle Q_{nB} Q_{nC} \rangle$ are found by considering all selected events, while the average $\langle Q_n^{D^0} Q_{nA}^{*} \rangle$ includes all $D^0$ meson candidates in all selected events.

To extract the inclusive $D^0$ meson flow harmonics, the individual $D^0$ candidates are divided into bins of their flow vector SP's (i.e., Eq. (1) but not averaged over all $D^0$ candidates). A separate mass spectrum is generated in each of these SP bins and an invariant mass fit is performed to get the SP distribution of the $D^0$ signal. The inclusive $D^0$ $v_n$ values can be obtained by:

$$v_n^{D^0} = \frac{\sum N_i Y_i}{\sum Y_i},$$

where $v_n^{D^0}$ is the center of the $i$-th SP bin, and the $Y_i$ is the $D^0$ yield in the same bin.

![Diagram](image_url)

Figure 1: An example of the fit to the invariant mass spectrum (left panel) and an example of the template fit of the inclusive $D^0$ meson yields, extracted as a function of DCA (right panel). The former fit is used for determining the total $D^0$ yields and the latter for determining the fraction of nonprompt $D^0$ mesons.

The $m_{inv}$ distributions are fitted with five components, as shown in Fig. 1, the sum of two Gaussian functions with the same mean but different widths for the $D^0$ signal, $S(m_{inv})$; an additional Gaussian function to describe the invariant mass shape of those $D^0$ candidates that were given an incorrect mass assignment when swapping the pion and kaon designations, $SW(m_{inv})$; two Crystal Ball functions [46] to describe the processes $D^0 \rightarrow \pi^+ \pi^-$ ($S(m_{\pi^+ \pi^-})$) and $D^0 \rightarrow K^+ K^-$ ($S(m_{K^+ K^-})$); and a third-order polynomial to model the combinatorial background, $Bkg(m_{inv})$.

The contributions from the processes $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^-$ are also resulting from using an incorrect $K$ or $\pi$ assignment. The ratio between the $S(m_{inv})$ and $SW(m_{inv})$ function yields is fixed according to values obtained from simulated events. The widths of the $S(m_{inv})$, $SW(m_{inv})$, and Crystal Ball functions are initialized by results obtained from simulation studies. They are allowed to vary with a single scale factor common to all three functions during the fit to data.

The fit of the invariant mass spectrum gives the yield for inclusive $D^0$ mesons. For the extraction of the two individual components (prompt and nonprompt), a similar procedure as in Refs. [47, 48] is followed. Distributions of the DCA between the $D^0$ meson momentum vector...
and primary vertex are fitted with a linear combination of prompt and nonprompt $D^0$ DCA templates obtained from MC in each bin of $p_T$, centrality, and $v_n$. The widths of the simulated distributions are scaled to match the data. The same scale factor is chosen for both prompt and nonprompt distributions by minimizing the $\chi^2$ of the template fit.

The left panel of Fig. 1 shows an example of a fit to the mass spectrum for $D^0$ candidates in the $p_T$ interval 6–8 GeV/c for the centrality class 30–50% and the SP range $0.4 < v_n < 0.5$. The right panel shows an example of the template fit of the inclusive $D^0$ meson yields, extracted as a function of DCA in the same $D^0$ kinematic region, but averaged over all $v_n$.

## 4 Systematic uncertainties

Systematic uncertainties are estimated by varying the conditions and procedures of the $v_n$ measurements. In the remaining discussion, numbers in parentheses give the absolute differences in $v_n$ between the nominal and the alternative analyses. In the fit to $m_{inv}$, the functional form of the combinatorial background was varied using a second-order polynomial and an exponential function (0.002 to 0.012). For the signal mass shape systematic check, a triple-Gaussian function is used and negligible differences are observed. The effect of the efficiency is studied by changing the efficiency correction values. In this alternative approach, the efficiency is based solely on simulation and does not consider any potential differences between the MC and data spectra (less than 0.0005). The systematic uncertainty from the determination of the nonprompt $D^0$ meson fraction is evaluated by performing the template fit using an alternative variable, the DCA significance ($DCA/(DCA\text{ uncertainty})$). In the case of DCA significance, the MC/data discrepancy is partially cancelled out by dividing DCA by its uncertainty. However, as DCA significance arises from the $D^0$ reconstruction, the widths of the distributions cannot be scaled to further match the data in the same way it was done for DCA. The difference in results between the DCA and DCA significance template fits is quoted as a systematic uncertainty. The largest uncertainty comes from this variation of the template fit (0.006 to 0.013). Systematic uncertainties in the BDT selection of the $D^0$ candidates are evaluated by studying MC samples. The difference between applying BDT selections and not applying those criteria is taken as the systematic uncertainty (0.001 to 0.006). The total systematic uncertainty is obtained by adding individual uncertainties in quadrature.

## 5 Results

The nonprompt $D^0$ meson flow harmonics are presented in Fig. 2 together with values for prompt $D^0$ mesons from Ref. [18]. The results show nonzero values of elliptic flow of $b$ mesons. The $v_2$ coefficient in the case of $b$ hadron daughters has its maximum value at $p_T$ of $\sim5$ GeV/c and is significantly lower than in the prompt $D^0$ meson case. This difference becomes more pronounced going from central to peripheral collisions. The observed mass ordering of collective flow agrees with the relation between charm and light quarks, where lighter particles exhibit higher flow. Measurements also suggest an increase of $v_2$ towards peripheral collisions, as in the case of light hadrons. This observation agrees with the paradigm of flow as a consequence of initial space anisotropy [10]. The elliptic flow of nonprompt $D^0$ mesons is found to be of the same magnitude as what the ATLAS Collaboration observed for nonprompt muons in the range $p_T > 10$ GeV/c [19].

The nonprompt $v_3$ coefficient results have large statistical uncertainties so that neither the $p_T$ nor the centrality dependence can be determined. However, an indication of a nonzero value is seen in the $4 < p_T < 6$ GeV/c range for all centralities. As was the case for $v_2$, the triangular
Figure 2: The elliptic, $v_2$ (upper panels), and the triangular, $v_3$ (lower panels), flow coefficients of nonprompt and prompt (from Ref. [18]) D$^0$ mesons as functions of their $p_T$ and in three bins of centrality. The bars and the boxes represent statistical and systematic uncertainties, respectively.

flow signal is weaker for nonprompt than for prompt D$^0$ mesons, but the difference is not as large as that for the elliptic flow. Measurements of b hadrons decaying into D$^0$ mesons suggest positive $v_3$ for D$^0$ mesons of $p_T \sim 5$ GeV/c. The ATLAS Collaboration $v_3$ results for b hadrons decaying into muons with $p_T > 4$ GeV/c were found to be consistent with zero [19].

Figure 3 shows the measured nonprompt D$^0$ meson $v_n$ coefficients compared with theoretical calculations that have different modeling of the b quark flow. The PHSD model is a microscopic off-shell transport model based on a Boltzmann transport equation approach, and includes only collisional energy loss [49]. The TAMU model computes the space-time evolution of the heavy-quark phase space distribution in the QGP using the Fokker–Planck equation, implemented via Langevin dynamics, and also has no radiative energy loss [52]. The LGR model uses the Langevin approach with glon radiation, emphasizing the in-medium diffusion dynamics. This model is best for describing heavy-quark evolutions from low to intermediate $p_T$ range, $p_T < 15$ GeV/c [53, 54]. The LBT model is based on a linearized Boltzmann approach coupled to a hydrodynamic background, and employs both collisional and radiative energy loss [50, 51]. The CUJET3.0 is essentially a jet energy loss framework based on a nonperturbative QGP medium [55, 56]. The LBT and CUJET3.0 approaches are applicable only for the high-$p_T$ range and do not have predictions for lower momenta. While all models can qualitatively describe the $p_T$ dependence of the data, the LGR model reproduces the measurements for the centrality 30–50% and in the low- and the intermediate-$p_T$ ranges, where b quarks follow Brownian motion, i.e., small random momentum fluctuations caused by collisions with thermal particles. For the central events, 0–10%, this model shows almost no $p_T$ dependence and does not predict the peak structure seen in the data. In the same $p_T$ range, the PHSD model provides a good description of the data, for centralities 0–10 and 10–30%, but it cannot describe the data at higher centralities. In contrast, this same PHSD model underpredicts the $v_2$ Fourier coefficients for D$^0$ mesons, which are not the product of b hadron decays [18]. The TAMU model has predictions in the centrality range 20–40%, therefore only an indirect comparison with data is possible, but the predictions describe well the measurement performed in the centrality range 10–30%. At higher $p_T$, where the anisotropy is driven by the path-length
dependence of parton energy loss, the LBT model gives lower predictions than CUJET3.0, but both models match data within uncertainties. The PHSD, LBT, and LGR models account for event-by-event fluctuations of the initial geometry, but PHSD is the only model that has predictions for \( v_3 \) coefficients. While precision is limited for both model and data, they reach similar maximal values in all centralities, with the exception that PHSD predicts the location of the maximum flow at a higher \( p_T \) than seen in data.

6 Summary

In summary, the elliptic \( (v_2) \) and triangular \( (v_3) \) flow harmonics of D\(^0\) mesons that originate in b hadron decays (nonprompt D\(^0\) mesons) are measured in lead-lead collisions at \( \sqrt{s}_{NN} = 5.02 \) TeV. The \( v_2 \) results show a weak transverse momentum \( (p_T) \) dependence and suggest a slight increase for more peripheral collisions. An indication of a nonzero \( v_3 \) coefficient is found for nonprompt D\(^0\) mesons with \( 4 < p_T < 6 \) GeV/c. The magnitudes of the flow coefficients are lower for nonprompt D\(^0\) than for prompt D\(^0\) mesons. This magnitude difference is more pronounced in the case of \( v_2 \). Comparisons of the results to theoretical models suggest a mass hierarchy in quark interactions with the quark-gluon plasma, thereby extending our understanding of heavy quark interactions with the medium.

References


