Elliptic Flow of Charm and Strange Hadrons in High-Multiplicity

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<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.121.082301">http://dx.doi.org/10.1103/PhysRevLett.121.082301</a></td>
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<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
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<td>Accessed</td>
<td>Sat Apr 06 05:39:36 EDT 2019</td>
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Elliptic Flow of Charm and Strange Hadrons in High-Multiplicity \( p + \text{Pb} \) Collisions at \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV

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(Received 25 April 2018; revised manuscript received 22 July 2018; published 21 August 2018)

The elliptic azimuthal anisotropy coefficient \( (v_2) \) is measured for charm \((D^0)\) and strange \((K^0_S, \Lambda, \Xi^-, \text{and} \Omega^-)\) hadrons, using a data sample of \( p + \text{Pb} \) collisions collected by the CMS experiment, at a nucleon-nucleon center-of-mass energy of \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV. A significant positive \( v_2 \) signal from long-range azimuthal correlations is observed for all particle species in high-multiplicity \( p + \text{Pb} \) collisions. The measurement represents the first observation of possible long-range collectivity for open heavy flavor hadrons in small systems. The results suggest that charm quarks have a smaller \( v_2 \) than the lighter quarks, probably reflecting a weaker collective behavior. This effect is not seen in the larger \( \text{PbPb} \) collision system at \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV, also presented.

DOI: 10.1103/PhysRevLett.121.082301

There has been long-standing interest in the space-time evolution of the multiparticle production process in high energy collisions of hadrons [1]. The observation of strong collective flow, as inferred from the correlations in azimuthal angle \((\phi)\) of particles emitted over a wide pseudorapidity \((\eta)\) range in relativistic nucleus-nucleus (AA) collisions, has been one of the key signatures suggesting the formation of a strongly interacting quark–gluon plasma (QGP) between the initial impact of the colliding nuclei and final production of particles. As observed first at the Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC) [2,2–5] and later at the CERN Large Hadron Collider (LHC) [6–11], the QGP exhibits nearly ideal hydrodynamical behavior [12–14]. In recent years, the observation of similar correlations in events with high final-state particle multiplicity resulting from proton-proton \((pp)\) [15–17] and proton-lead \((p + \text{Pb})\) [18–21] collisions at the LHC has raised the question whether a fluidlike QGP is also created in these smaller collision systems [22].

The azimuthal correlation structure of emitted particles is typically characterized by its Fourier components [23]. In hydrodynamic models, the second and third Fourier components, known as elliptic \((v_2)\) and triangular \((v_3)\) flow, respectively, most directly reflect the QGP response to the initial collision geometry and its fluctuations [24–26]. The properties of the long-range correlation associated with light-flavor and strange hadrons in small systems are found to be similar to those observed in AA collisions. This includes, e.g., the particle species dependence [27–29] and multiparticle (or collective) nature [29–32] of the long-range correlation. More recently, such long-range correlations have also been observed in lighter systems at RHIC, including \( d\text{Au} \) [33–35] and \( ^3\text{HeAu} \) [36]. While these measurements are consistent with a hydrodynamic expansion, alternative scenarios based on gluon saturation in the initial state also claim to capture the main features of the correlation data (recent reviews are provided in Refs. [37,38]).

The large masses of heavy quarks (charm and bottom) lead to their being produced in the early stages of the collision, and they thus probe the properties of the QGP through their interactions with the medium [39]. The elliptic flow results for \( D \) mesons in AA collisions measured at RHIC [40] and the LHC [41–43] suggest that charm quarks develop strong collective behavior, similar to the bulk production of light flavor particles from the QGP. In small systems, long-range correlation involving inclusive muons and \( J/\psi \) mesons have revealed hints of heavy flavor quark collectivity [44,45]. Observation of \( D \) meson \( v_2 \) in the \( p + \text{Pb} \) system, and especially the comparison to the light-flavor and strange particle \( v_2 \), can impose further constraints on different interpretations related to the origin of the observed long-range collectivity. In particular, such measurements can provide key insights into properties of heavy quark interaction and thermalization within a hot QGP medium possibly formed at a significantly reduced system size.

This Letter presents the first measurements of the elliptic anisotropies of prompt \( D^0 \) mesons and strange hadrons \((K^0_S, \Lambda, \Xi^-, \text{and} \Omega^-)\) in \( p + \text{Pb} \) collisions at a nucleon-nucleon center-of-mass energy of \( \sqrt{s_{\text{NN}}} = 8.16 \) TeV. In all cases, particles and antiparticles are combined in the

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\(^{\ast}\)Full author list given at the end of the Letter.

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DOI: 10.1103/PhysRevLett.121.082301
the relevant kinematic variables, can be found in Ref. [47].

A detailed description of the CMS detector, together with a definition of the coordinate system used and parameter [46]. 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, there are four primary subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Iron and quartz-fiber Cherenkov hadron forward calorimeters cover the range $2.9 < |\eta| < 5.2$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For charged particles with $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in $p_T$ and 25–90 (45–150) $\mu$m in the transverse (longitudinal) impact parameter [46]. A 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. [47].

The $p+\text{Pb}$ data at $\sqrt{s_{\text{NN}}} = 8.16$ TeV used in this analysis were collected by the CMS experiment in 2016, and correspond to an integrated luminosity of 186 nb$^{-1}$. The beam energies are 6.5 TeV for the protons and 2.56 TeV per nucleon for the lead nuclei. Because of the asymmetric beam conditions, particles selected in this Letter from midrapidity in the laboratory frame ($|y_{\text{lab}}| < 1$) correspond to rapidity in the nucleon–nucleon center-of-mass frame of $-1.46 < y_{\text{cm}} < 0.54$, with positive rapidity corresponding to the proton beam direction. The event reconstruction, event selections, and triggers are identical to those described in Refs. [48,49]. A subset of PbPb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for 30%–50% centrality were also used and reprocessed using the same reconstruction algorithm as the $p+\text{Pb}$ data.

The $p+\text{Pb}$ data are analyzed for multiplicity ranges of $N_{\text{trk}}^{\text{offline}} < 35$ and $185 \leq N_{\text{trk}}^{\text{offline}} < 250$, where $N_{\text{trk}}^{\text{offline}}$ is the number of primary tracks [46] with $|\eta| < 2.4$ and $p_T > 0.4$ GeV. Events in the multiplicity region of $N_{\text{trk}}^{\text{offline}} > 250$ is not included to avoid effects of multiple interactions in a single event (pileup). Several topological selections are applied to further reduce the combinatorial background. In particular, strange hadron and $D^0$ candidates are selected according to the $\chi^2$ probability of their decay vertex, the three-dimensional distance (normalized by its uncertainty) between the primary and decay vertices, and the pointing angle (defined as the angle between the line segment connecting the primary and decay vertices and the momentum vector of the reconstructed particle candidates in the plane transverse to the beam direction). The selection is optimized in each $p_T$ bin, separately for different particle species, in order to maximize the statistical significance of the signal. For $\Xi^-$ and $\Omega^-$ reconstruction, these selections are applied to both the initial decay vertex and the subsequent decay vertex of $\Lambda$.

In the case of the $D^0$ measurement, the selections on the pointing angle also suppress the fraction of nonprompt $D^0$ production (from decays of $b$ hadrons). Simulated event samples of PYTHIA 8.209 [52,53] $D^0$ signal events, embedded into EPOS LHC [54] minimum bias $p+\text{Pb}$ events, are used to estimate the nonprompt $D^0$ contamination in data. By fitting the distributions of distance of closest approach of $D^0$ total momentum vector to the primary vertex, using the probability distribution functions (pdf) for prompt and nonprompt $D^0$ derived from simulation, the residual nonprompt fraction is found to be decreasing with $p_T$ from 7% to 1%.

The azimuthal anisotropies of $D^0$ mesons and strange hadrons are extracted from their long-range ($|\Delta\eta| > 1$)
two-particle azimuthal correlations with charged particles, as described in Refs. [28,29]. Taking the $D^0$ meson as an example, the two-dimensional (2D) correlation function is constructed by pairing each $D^0$ candidate with reference primary charged-particle tracks with $0.3 < p_T < 3.0$ GeV (denoted “ref” particles), and calculating

$$\frac{1}{N_{D^0}} \frac{d^2N_{\text{pair}}}{d\Delta \eta d\Delta \phi} = B(0,0) \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} , \tag{1}$$

where $\Delta \eta$ and $\Delta \phi$ are the differences in $\eta$ and $\phi$ of each pair. The same-event pair distribution, $S(\Delta \eta, \Delta \phi)$, represents the yield of particle pairs normalized by the number of $D^0$ candidates from the same event. The mixed-event pair yield distribution, $B(\Delta \eta, \Delta \phi)$, is constructed by pairing $D^0$ candidates in each event with the reference primary charged-particle tracks from 20 different randomly selected events, from the same $N_{\text{trk}}^\text{offline}$ range, and with a primary vertex falling in the same 2 cm wide range of reconstructed $z$ coordinate. The analysis procedure is performed in each $D^0$ candidate $p_T$ range by dividing it into intervals of invariant mass. The correction for acceptance and efficiency (derived from PYTHIA+EPOS simulations) of the $D^0$ meson yield is found to have negligible effect on the measurements, and thus is not applied. The $\Delta \phi$ correlation functions averaged over $|\Delta \eta| > 1$ (to remove short-range correlations such as jet fragmentation) is then obtained from the projection of 2D distributions and fitted by the first three terms of a Fourier series (including additional terms has a negligible effect):

$$\frac{1}{N_{D^0}} \frac{dN_{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left(1 + \sum_{n=1}^{3} 2V_n \Delta \cos(n \Delta \phi) \right). \tag{2}$$

Here, $V_n \Delta$ are the Fourier coefficients and $N_{\text{assoc}}$ represents the total number of pairs per $D^0$ candidate. By assuming $V_n \Delta$ to be the product of single-particle anisotropies [55], $V_n \Delta(D^0, \text{ref}) = v_n(D^0) v_n(\text{ref})$, the $v_n$ anisotropy harmonics for $D^0$ candidates can be extracted as a function of invariant mass, $v_n(D^0) = V_n \Delta(D^0, \text{ref}) / \sqrt{V_{n\Delta}(\text{ref})}$. Because of the limited amount of available data, only the elliptic anisotropy harmonic is measured. The residual contribution of back-to-back dijets to the measured $v_2$ results is corrected by subtracting correlations from low-multiplicity $p + Pb$ events, following an identical procedure established in Refs. [29,55]. The Fourier coefficients, $V_n \Delta$, extracted from events with $N_{\text{trk}}^\text{offline} < 35$ are subtracted from those extracted from events with $185 \leq N_{\text{trk}}^\text{offline} < 250$ after accounting for the jet yield ratio of the selected events. The subtraction is not performed for PbPb results as the back-to-back jet correlations are found to be negligible in events with centrality between 30% and 50% [49].

To extract the $v_2$ values of the $D^0$ meson signal ($v_2^S$), a simultaneous fit to the invariant mass spectrum of $D^0$ candidates and their $v_2$ as a function of the invariant mass, $v_2^{S+B}(m_{\text{inv}})$, is performed in each $p_T$ interval. The mass spectrum fit function is composed of three components: the sum of two Gaussian functions with the same mean but different widths for the $D^0$ signal, $S(m_{\text{inv}})$, an additional Gaussian function to describe the invariant mass shape of $D^0$ candidates with an incorrect mass assignment from the exchange of the pion and kaon designations, $SW(m_{\text{inv}})$, and a third-order polynomial to model the combinatorial background, $B(m_{\text{inv}})$. The width of $SW(m_{\text{inv}})$ and the ratio of the yields of $SW(m_{\text{inv}})$ and $S(m_{\text{inv}})$ are fixed according to results obtained from PYTHIA+EPOS simulation studies. The $v_2^{S+B}(m_{\text{inv}})$ distribution is fitted with

$$v_2^{S+B}(m_{\text{inv}}) = \alpha(m_{\text{inv}}) v_2^S + [1 - \alpha(m_{\text{inv}})] v_2^B(m_{\text{inv}}), \tag{3}$$

where

$$\alpha(m_{\text{inv}}) = \frac{S(m_{\text{inv}}) + SW(m_{\text{inv}})}{S(m_{\text{inv}}) + SW(m_{\text{inv}}) + B(m_{\text{inv}})} . \tag{4}$$

Here $v_2^B(m_{\text{inv}})$ for the background $D^0$ candidates is modeled as a linear function of the invariant mass, and $\alpha(m_{\text{inv}})$ is the $D^0$ signal fraction. The $K$-$\pi$ swapped component is included in the signal fraction because these candidates are from genuine $D^0$ mesons and should have the same $v_2$ value as that of the nonswapped $D^0$ signal. Figure 1 shows an example of a simultaneous fit to the mass spectrum and $v_2^{S+B}(m_{\text{inv}})$ in the $p_T$ interval 4.2–5.0 GeV for the multiplicity range $185 \leq N_{\text{trk}}^\text{offline} < 250$ in $p + Pb$
collisions. The $v_2$ values for the strange hadrons are extracted in the same way although no swapped-mass component is required.

As the residual contribution from nonprompt $D^0$ mesons is small, no explicit correction is applied and a systematic uncertainty is quoted instead. Based on the prediction for AA collisions that $B$ mesons have a smaller $v_2$ than light-flavor particles, due to the larger mass of the b quark [56–58], the nonprompt $D^0$ $v_2$ values are assumed to lie between 0 and those of strange hadrons. The maximum effect from nonprompt $D^0$ mesons is thus estimated using the extracted nonprompt $D^0$ fraction and the change in $v_2^S$ is found to be smaller than 6%.

Other sources of systematic uncertainty in the $D^0$ $v_2$ measurement in this analysis include the background mass pdf, the $D^0$ meson yield correction (acceptance and efficiency correction), selection of the $D^0$ candidates, and the background $v_2$ pdf. No systematic effect has been observed while changing the background mass pdf to a second-order polynomial function of the invariant mass. To evaluate the uncertainties arising from the $D^0$ meson yield correction, the $v_2$ values are extracted from the corrected signal $D^0$ distributions and compared to the uncorrected $v_2$ values, yielding an uncertainty of 2%. The selection criteria for $D^0$ candidates are also varied to tighter and looser values such that the $D^0$ signal fraction, $a_0(m_{inv})$, changes by 50% and a systematic uncertainty of 14% is evaluated from the variations of $v_2$. The systematic uncertainties from the background $v_2$ pdf (20% for $p_T < 2.4$ GeV and 4% for $p_T > 2.4$ GeV) are evaluated by changing $v_2^B(m_{inv})$ to a second-order polynomial function of the invariant mass and a constant value. Systematic uncertainties from trigger bias and effects of pileup are negligible.

For $K_S^0$, $\Lambda$, and $\Xi^-$ particles, the systematic uncertainties related to selection of reconstructed candidates (2% for $K_S^0$ and $\Lambda$ particles and 6% for $\Xi^-$ particles) are evaluated in the same way as for $D^0$ mesons. To test the procedure of extracting the signal $v_2$, a study using EPOS LHC [54] $p +$ Pb events is performed and the extracted values are compared to the generator-level values. The agreement is found to be better than 6%. Systematic uncertainties for $\Omega^-$ particles are quoted to be the same as those of $\Xi^-$ particles.

Figure 2 shows the results of the $v_2$ measurement of the prompt $D^0$ meson with $-1.46 < y_{cm} < 0.54$ for high-multiplicity (185 $\leq N_{\text{offine}} < 250$) $p +$ Pb collisions. The $v_2$ results for strange hadrons are also shown for comparison. A clear mass ordering in the elliptic flow is observed in the low-$p_T$ region of $\leq 2.5$ GeV, where heavier particle species have a smaller $v_2$ signal at a given $p_T$ value. For $p_T > 2.5$ GeV, $v_2$ values for $\Lambda$, $\Xi^-$, and $\Omega^-$ baryons, which are similar to each other, all become larger than those of $D^0$ and $K_S^0$ mesons, a trend which is also observed in 5.02 TeV $p +$ Pb collisions [28].

![Graph showing the elliptic flow ($v_2$) for $D^0$ mesons as a function of $p_T$ (GeV) and $N_{\text{offline}}$]
universal scaling of $v_2/n_q$ between mesons and baryons is observed. The behavior is qualitatively different in the larger PbPb collision system with centrality between 30% and 50%. The results for all particle species tend to follow a common trend in the $KE_T/n_q < 1$ GeV region, indicating that $D^0$ mesons develop a strong collective behavior similar to the bulk of the QGP.

In summary, the first measurements of elliptic azimuthal anisotropies for prompt $D^0$ mesons, as well as $K^0_S$, $\Lambda$, $\Xi^-$, $\Omega^-$ hadrons, in high-multiplicity $p+Pb$ collisions at $\sqrt{s_{NN}} = 8.16$ TeV are presented. Significant positive $v_2$ values are observed for $D^0$ mesons with $p_T > 2$ GeV. Comparing to strange-hadron results, the $D^0$ $v_2$ values are found to be smaller at a given $p_T$, or at similar transverse kinetic energy per constituent quark, after normalizing $v_2$ by the number of constituent quarks. The latter effect is not observed in the larger PbPb collision system. A possible interpretation is that, in high multiplicity $p+Pb$ collisions, in contrast to larger nucleus-nucleus collision systems, the collective behavior of charm quarks is weaker than that of the light-flavor quarks.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).


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