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Azimuthal anisotropy of heavy-flavour decay electrons in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

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Abstract

Angular correlations between heavy-flavour decay electrons and charged particles at mid-rapidity ($|\eta| < 0.8$) are measured in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The analysis is carried out for the 0–20% (high) and 60–100% (low) multiplicity ranges. The jet contribution in the correlation distribution from high-multiplicity events is removed by subtracting the distribution from low-multiplicity events. An azimuthal modulation remains after removing the jet contribution, similar to previous observations in two-particle angular correlation measurements for light-flavour hadrons. A Fourier decomposition of the modulation results in a positive second-order coefficient (v_2) for heavy-flavour decay electrons in the transverse momentum interval $1.5 < p_{\rm T} < 4$ GeV/c in high-multiplicity events, with a significance larger than 5σ. The results are compared with those of charged particles at mid-rapidity and of inclusive muons at forward rapidity. The v_2 measurement of open heavy-flavour particles at mid-rapidity in small collision systems could provide crucial information to help interpret the anisotropies observed in such systems.

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* See Appendix A for the list of collaboration members

Two-particle angular correlations are a powerful tool to study the dynamical evolution of the system created in ultra-relativistic collisions of protons or nuclei. The differences in the azimuthal angle ($\Delta\varphi$) and in pseudorapidity ($\Delta\eta$) between a reference ("trigger") particle and other particles produced in the event are considered. The typical shape of the correlation distribution features a near-side peak at $(\Delta\varphi, \Delta\eta) \sim (0,0)$, induced by the jet containing the trigger particle, and an away-side structure centered at $\Delta\varphi \sim \pi$ and extending over a wide pseudorapidity range, due to the recoil jet [1]. In nucleus–nucleus collisions the correlation distribution also exhibits pronounced structures on the near- and away-side extending over a large $\Delta\eta$ region, commonly referred to as "ridges" [2]. The $\Delta\varphi$ projection of the correlation distribution, after removal of the jet contribution, can be described by a Fourier decomposition, whose coefficients are denoted as $V_{\mathrm{n}\Delta}$. These coefficients can be factorised into single-particle coefficients v_{n} related to the azimuthal distribution of the particles with respect to the reaction plane of the collision [3]. In non-central nucleus–nucleus collisions, the dominant coefficient is that of the second-order harmonic, referred to as elliptic flow (v_2), and its value is used to characterise the collective motion of the system. The measurements are well described by models invoking a hydrodynamic expansion of the hot and dense medium produced in the collision. This translates the initial-state spatial anisotropy, due to the asymmetry of the nuclear overlap region, into a momentum anisotropy of the particles emerging from the medium [4]. This collective motion is one of the important features of the Quark-Gluon Plasma (QGP) produced in such collisions.

Surprisingly, the presence of similar long-range ridge structures and a positive v_2 coefficient were also observed for light-flavour hadrons in high-multiplicity proton–lead (p–Pb) collisions by the ALICE [5], ATLAS [6] and CMS [7] collaborations at the LHC. The pattern of the v_2 coefficient as a function of the particle mass and transverse momentum is similar in p–Pb and Pb–Pb collisions [8, 9]. The PHENIX and STAR collaborations at RHIC also measured a positive v_2 coefficient for charged hadrons in high-multiplicity deuteron–gold collisions [10, 11]. A near-side structure extended over a large $\Delta\eta$ range was also reported for high-multiplicity proton–proton (pp) collisions by the CMS [12] and ATLAS [6] collaborations. The interpretation of a positive v_2 in these small collision systems is currently highly debated [13]. One possible interpretation is based on collective effects induced by a hydrodynamical evolution of the particles produced in the collision [14, 15]. Other approaches include mechanisms involving initial-state effects, such as gluon saturation within the Color-Glass Condensate effective field theory [16, 17], or final-state colour-charge exchanges [18, 19].

Because of their large masses, heavy quarks are produced in hard scattering processes during the early stages of hadronic collisions [20]. In Pb–Pb collisions, the elliptic flow of charm mesons [21–23] and heavy-flavour decay leptons [24, 25] was found to have similar magnitude as that of charged particles [26], dominated by light-flavour hadrons. A search for a non-zero v_2 in the correlation pattern of heavy-flavour particles in high-multiplicity p–Pb collisions could provide further insight on the initial- and final-state origin of the anisotropies in this collision system, helping in constraining the models that describe the ridge structures. The production mechanisms of heavy quarks, involving a large squared four-momentum transfer, are also different from those of light-flavour quarks. This gives the possibility to investigate whether the onset of the anisotropy of the particle azimuthal distribution is affected by the details of hard scattering and fragmentation processes.

In this letter, we present the measurement of v_2 for open heavy-flavour particles at mid-rapidity in high-multiplicity p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV via azimuthal correlations of electrons from charm- and beauty-hadron decays, and charged particles. This result complements our previous studies of hidden-charm particles based on the measurement of the correlations between J/ψ mesons at forward rapidity and charged particles at mid-rapidity in high-multiplicity p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and 8.16 TeV, which found evidences for a positive v_2 for J/ψ mesons [27]. The ALICE collaboration also measured a positive v_2 for muons at forward and backward rapidity, which are predominantly produced by heavy-flavour decays for transverse momentum (p_{T}) greater than 2 GeV/c, in high-multiplicity p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [28]. Similar indications of positive v_2 were also reported at mid-rapidity in high-multiplicity p–Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV for $\rm D^0$ mesons by the CMS [29] collaboration and in preliminary results for $\rm D^{*+}$ mesons [30] and heavy-flavour decay muons [31] by the ATLAS collaboration.

The data sample used for the analysis was collected by the ALICE experiment [32, 33] in 2016 during the LHC p–Pb run at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The center-of-mass reference frame of the nucleon–nucleon collision was shifted in rapidity by 0.465 units in the proton-going direction with respect to the laboratory frame. The events were recorded using a minimum-bias trigger, which required coincident signals in the two scintillator arrays of the V0 detector, covering the full azimuthal angle in the pseudorapidity (η) ranges $2.8 < \eta < 5.1$ (V0-A) and $-3.7 < \eta < -1.7$ (V0-C). Together with the V0 information, signals from the two Zero-Degree Calorimeters (ZDCs) were used to reject beam-induced background. Only events with a primary vertex reconstructed within ± 10 cm from the center of the detector along the beam axis were accepted. After this selection, about 6×10^8 events, corresponding to an integrated luminosity of $L_{\rm int} = 295 \pm 11\ \mu{\rm b}^{-1}$, were used in this analysis. Only events in high- (0–20%) and low-multiplicity (60–100%) classes, evaluated using the amplitude of the signal in the V0-A detector [34], were considered.

Electrons with transverse momentum ($p_{\rm T}^{\rm e}$) in the interval $1.5 < p_{\rm T}^{\rm e} < 6$ GeV/c and $|\eta| < 0.8$ (corresponding to $-1.26 < y_{\rm cms}^{\rm e} < 0.34$, where $y_{\rm cms}^{\rm e}$ is the rapidity of the electron in the center-of-mass reference frame) were selected using similar criteria as discussed in [35]. Charged tracks were reconstructed using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) . The ITS comprises six layers of silicon detectors, with the two innermost layers composed of pixel detectors. The TPC is a gaseous detector and the main tracking device, measuring up to 159 space points per track. Tracks were required to have hits on both pixel layers of the ITS to reduce the contamination of electrons from photon conversions in the detector material. In order to reject secondary electrons [36], produced in interactions with the detector material or from particle weak decays, the tracks were required to have a distance of closest approach to the primary vertex of less than 1 cm along the beam axis and 0.25 cm in the transverse plane. The particle identification employed a selection on the specific ionisation energy loss inside the TPC of $-1 < n_\sigma^{\rm TPC} < 3$, where n_σ is the difference between the measured and expected detector response signals for electrons normalised to the response resolution. A selection ($-3 < n_\sigma^{\rm TOF} < 3$) was also applied using the Time of Fight (TOF) detector, a set of multigap resistive plate chambers that can separate hadrons and electrons at low momentum via time-of-flight measurement. The electron reconstruction efficiency was calculated using Monte Carlo simulations of events containing $\rm c\bar{c}$ and $\rm b\bar{b}$ pairs generated with PYTHIA 6.4.21 [37] and the Perugia-2011 tune [38], and an underlying p-Pb collision generated using HIJING 1.36 [39]. The generated particles were propagated through the detector using the GEANT3 transport package [40]. With the selections described above, the resulting electron reconstruction efficiency is about 28% at $p_{\rm T}^{\rm e} = 1.5$ GeV/c, growing to about 32% at $p_{\rm T}^{\rm e} = 6$ GeV/c. The contamination from charged hadrons was determined as described in [41] and estimated to be about 1% (10%) for $1.5 < p_{\rm T}^{\rm e} < 4$ GeV/c ($4 < p_{\rm T}^{\rm e} < 6$ GeV/c).

The selected electrons are composed of signal heavy-flavour decay electrons (HFe), originating from semi-leptonic decays of open heavy-flavour hadrons, and background electrons. The main background sources are photon conversions ($\gamma \rightarrow {\rm e^+e^-}$) in the beam vacuum tube and in the material of the innermost layers of the ITS and Dalitz decays of neutral mesons ($\pi^0 \rightarrow \gamma\, {\rm e^+e^-}$ and $\eta \rightarrow \gamma\, {\rm e^+e^-}$), defined as non-heavy-flavour decay electrons (NonHFe) hereafter. Contributions of electrons from other background sources, such as other Dalitz decays or decays of kaons and J/ψ mesons, are negligible in the $p_{\rm T}$ range studied in the analysis [35] and were not considered. To estimate the background contribution, di-electron pairs were defined by pairing the selected electrons with opposite-charge electron partners to form unlike-signed pairs (ULS) and calculating their invariant mass ($M_{\rm e^+e^-}$). Partner electrons were selected applying similar but less stringent track quality and particle identification criteria than those used for selecting signal electrons. The di-electron pairs from NonHFe sources have a small invariant mass, while heavy-flavour decay electrons can form ULS pairs mainly through random combinations with other electrons, resulting in a continuous invariant-mass distribution. The combinatorial contribution was estimated from the invariant mass distribution of like-signed electron (LS) pairs. The NonHFe background contribution was then evaluated by subtracting the LS distribution from the ULS distribution in the invariant mass region $M_{\mathrm{e^+e^-}} < 140$ MeV/c^2. More details on the procedure can be found in [35, 42]. The efficiency of finding the partner electron to identify non-heavy-flavour decay electrons ($\varepsilon_{\mathrm{NonHFe}}$) was calculated with the aforementioned Monte Carlo simulations, and is about 60% for $1.5 < p_{\mathrm{T}}^{\mathrm{e}} < 2$ GeV/c, rising to 76% for $4 < p_{\mathrm{T}}^{\mathrm{e}} < 6$ GeV/c.

The number of heavy-flavour decay electrons (N_{HFe}) can be expressed as:

$$N_{\mathrm{HFe}} = N_{\mathrm{e}} - N_{\mathrm{NonHFe}} = N_{\mathrm{e}} - \frac{1}{\varepsilon_{\mathrm{NonHFe}}}(N_{\mathrm{ULSe}} - N_{\mathrm{LSe}}), \tag{1}$$

where N_{ULSe} and N_{LSe} are the number of electrons which form unlike-sign and like-sign pairs, respectively, with $M_{\mathrm{e^+e^-}} < 140$ MeV/c^2, and N_{e} is the number of selected electrons.

The two-particle correlation distributions between electrons (trigger) and charged (associated) particles were obtained for three different $p_{\mathrm{T}}^{\mathrm{e}}$ intervals ($1.5 < p_{\mathrm{T}}^{\mathrm{e}} < 2$ GeV/c, $2 < p_{\mathrm{T}}^{\mathrm{e}} < 4$ GeV/c and $4 < p_{\mathrm{T}}^{\mathrm{e}} < 6$ GeV/c). Associated charged particles with $0.3 < p_{\mathrm{T}}^{\mathrm{ch}} < 2$ GeV/c and $|\eta| < 0.8$ were selected with similar criteria as used for electrons, apart from requiring a hit in at least one, instead of both, of the two pixel layers and not applying any particle identification. The single-track reconstruction efficiency and the contamination from secondary particles [36] were estimated using Monte Carlo simulations of p–Pb collisions produced with the DPMJET 3.0 event generator [43] and GEANT3 [40] for the particle transport. Both were found to be independent of the event multiplicity. With the selections described above, the tracking efficiency varies from 75% to 85% depending on track momentum and primary vertex position, and the contamination of secondary particles varies from 3% to 5.5% with decreasing p_{T} of the charged particle.

The $(\Delta\varphi, \Delta\eta)$ correlation distribution between heavy-flavour decay electrons and charged particles is obtained with the equation:

$$\begin{aligned} S_{\mathrm{HFe}} &= S_{\mathrm{e}} - S_{\mathrm{NonHFe}} \\ &= S_{\mathrm{e}} - S_{\mathrm{NonHFe}}^{\mathrm{ID}} - S_{\mathrm{NonHFe}}^{\mathrm{nonID}} \\ &= S_{\mathrm{e}} - S_{\mathrm{NonHFe}}^{\mathrm{ID}} - \left(\frac{1}{\varepsilon_{\mathrm{NonHFe}}} - 1\right) S_{\mathrm{NonHFe}}^{\mathrm{ID*}}, \end{aligned} \tag{2}$$

where S corresponds to $\mathrm{d}^2N_{\mathrm{e-ch}}(\Delta\eta, \Delta\varphi)/\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi$. The correlation distributions for all trigger electrons and for non-heavy-flavour decay trigger electrons are denoted as S_{e} and S_{NonHFe}, respectively. The hadron contamination in S_{e} is statistically removed by subtracting a scaled di-hadron correlation distribution. The S_{NonHFe} distribution is evaluated from its two contributions $S_{\mathrm{NonHFe}}^{\mathrm{ID}}$ and $S_{\mathrm{NonHFe}}^{\mathrm{nonID}}$. The former corresponds to correlations from background electron triggers with an identified electron partner, and the latter to the expected contribution from background trigger electrons without an identified partner. The identified background distribution, $S_{\mathrm{NonHFe}}^{\mathrm{ID}}$, is evaluated using correlations of trigger electrons paired with unlike-sign and like-sign electrons, with a similar procedure as that used to evaluate N_{NonHFe} (see Eq. 1). The non-identified distribution, $S_{\mathrm{NonHFe}}^{\mathrm{nonID}}$, is estimated assuming that both identified and non-identified NonHFe triggers have the same correlation distribution, apart from reconstructed partner electrons used to calculate $M_{\mathrm{e^+e^-}}$, which are removed from $S_{\mathrm{NonHFe}}^{\mathrm{ID}}$ to obtain $S_{\mathrm{NonHFe}}^{\mathrm{ID*}}$.

The correlation distribution for heavy-flavour decay electrons was corrected for the electron and charged particle efficiencies and for the secondary particle contamination. It was also corrected for the limited

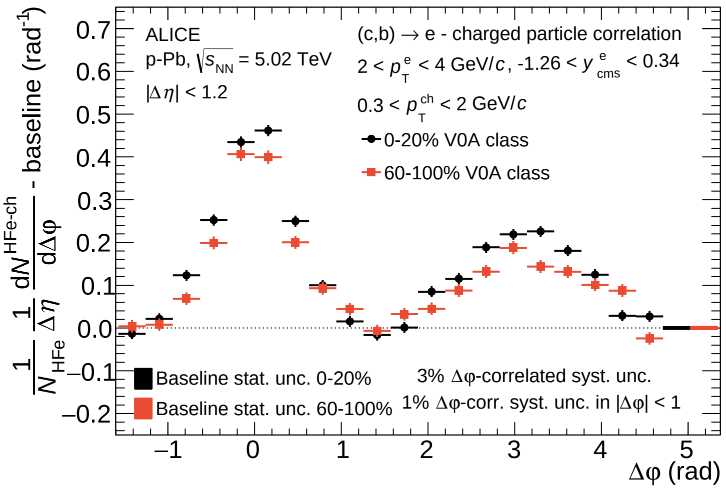

Fig. 1: Azimuthal correlations between heavy-flavour decay electrons and charged particles, for high-multiplicity and low-multiplicity p–Pb collisions, after subtracting the baseline (see text for details) for $2 < p_{\mathrm{T}}^{\mathrm{e}} < 4$ GeV/c and $0.3 < p_{\mathrm{T}}^{\mathrm{ch}} < 2$ GeV/c. Statistical uncertainties are shown as error bars. The statistical uncertainties on the baseline subtraction are represented as boxes at $\Delta\varphi \approx 5$.

two-particle acceptance and detector inhomogeneities using the event mixing technique [8]. The mixed-event correlation distribution was obtained by combining electrons in an event with charged particles from other events with similar multiplicity and primary vertex position. The correlation distribution for heavy-flavour decay electrons was divided by the number of heavy-flavour decay trigger electrons (N_{HFe}, from Eq. 1) corrected by their reconstruction efficiency.

The two-dimensional correlation distribution was projected onto $\Delta\varphi$ for $|\Delta\eta| < 1.2$ and divided by the width of the selected $\Delta\eta$ interval. In order to compare the jet-induced peaks from different multiplicity ranges, a "baseline" term, constant in $\Delta\varphi$, was calculated from the weighted average of the three lowest points of the correlation distribution (following the zero yield at minimum, ZYAM, approach [44]) and was subtracted from it. The resulting correlation distributions in the two considered multiplicity classes (0–20% and 60–100%) are shown in Fig. 1 for the interval $2 < p_{\mathrm{T}}^{\mathrm{e}} < 4$ GeV/c. An enhancement of the near- and away-side peaks is present in high-multiplicity collisions. To study this feature, the baseline-subtracted correlation distribution obtained in low-multiplicity events was subtracted from the correlation distribution measured in high-multiplicity events, as described in [5]. This removes the jet-induced correlation peaks, under the assumption that they are the same in low- and high-multiplicity events. The correlation distribution was restricted to the $(0,\pi)$ range by reflecting the symmetrical points. The resulting distribution shows an azimuthal anisotropy compatible with the presence of a dominant second-order ($V_{2\Delta}^{\mathrm{HFe-ch}}$) modulation in its Fourier decomposition, as shown in Fig. 2. The $V_{2\Delta}^{\mathrm{HFe-ch}}$ coefficient was quantified by fitting the distribution with the function in Eq. 3. The measured $V_{2\Delta}^{\mathrm{HFe-ch}}$ in high-multiplicity events does not exclude the possibility of having a $V_{2\Delta}^{\mathrm{HFe-ch}}$ contribution in the low-multiplicity events, as described in [6].

$$\frac{1}{\Delta\eta}\frac{1}{N_{\mathrm{HFe}}}\frac{\mathrm{d}N_{\mathrm{HFe-ch}}(\Delta\varphi)}{\mathrm{d}\Delta\varphi} = a[1 + 2V_{1\Delta}^{\mathrm{HFe-ch}}\cos(\Delta\varphi) + 2V_{2\Delta}^{\mathrm{HFe-ch}}\cos(2\Delta\varphi)] \quad (3)$$

The systematic uncertainties on the azimuthal correlation distribution can originate from: (i) potential biases in the procedure employed to select electron candidates and estimate the hadron contamination, (ii) removal of the background electrons not produced in heavy-flavour hadron decays and (iii) choice of the associated particle selection. A systematic uncertainty related to the electron reconstruction efficiency arises from imprecisions in the description of the detector response. It was studied by varying the electron selection in the ITS and TPC. The uncertainty affecting the removal of the hadron contamination was estimated by varying the particle identification criteria in the TPC ($n_{\sigma}^{\mathrm{TPC}}$). A total uncertainty of less than 0.5% was estimated from these sources. The uncertainty related to the efficiency of finding the partner electron and to the stability of the S_{NonHFe} distribution, evaluated from its two contributions $S_{\mathrm{NonHFe}}^{\mathrm{ID}}$ and $S_{\mathrm{NonHFe}}^{\mathrm{nonID}}$, was studied by varying the selection for partner tracks and pair invariant mass, resulting in an uncertainty of less than 0.5%. The uncertainty on the associated track reconstruction efficiency, obtained by varying the associated track selection criteria and by comparing the probabilities of track prolongation from TPC to ITS in data and simulations, was estimated to be 3% [45]. A systematic effect due to the contamination of the associated particles by secondaries comes from residual discrepancy between Monte Carlo and data in the relative abundances of particle species and was studied by varying the selection on the distance of closest approach to the primary vertex. It was quantified to be 1% (correlated in $\Delta\varphi$), with an additional 1% (correlated) for $|\Delta\varphi| <1$. Combining the uncertainties from all the above sources results in a 3% total systematic uncertainty (correlated in $\Delta\varphi$) and an additional 1% (also correlated) for $|\Delta\varphi| < 1$.

The systematic uncertainties from the above mentioned sources are also present in the $V_{2\Delta}^{\mathrm{HFe-ch}}$. The uncertainty related to the electron selection and the identification of non-heavy-flavour decay electrons on $V_{2\Delta}^{\mathrm{HFe-ch}}$ were quantified to be about 2–3% and 5%, respectively. The contamination of the associated particles by secondaries leads to a 3% systematic uncertainty. In order to test whether the observed modulation and the non-zero $V_{2\Delta}^{\mathrm{HFe-ch}}$ could originate from a residual jet contribution, due to possible differences between the jet structures in low- and high-multiplicity collisions, the $\Delta\eta$ range used to obtain the $\Delta\varphi$ projection was varied by introducing a pseudorapidity gap. The observed variation on $V_{2\Delta}^{\mathrm{HFe-ch}}$ was 11–15%, depending on the electron p_{T} interval, and was taken as the systematic uncertainty from the jet subtraction. The stability of the $V_{2\Delta}^{\mathrm{HFe-ch}}$ value against the variation of the $\Delta\eta$ range suggests a long-range nature of the observed anisotropy. The inclusion of a $V_{3\Delta}^{\mathrm{HFe-ch}}$ term in the fit function, in Eq. 3, affects the $V_{2\Delta}^{\mathrm{HFe-ch}}$ estimation by less than 0.5%. Combining the different uncertainty sources results in a total systematic uncertainty on $V_{2\Delta}^{\mathrm{HFe-ch}}$ of 13–16% depending on $p_{\mathrm{T}}^{\mathrm{e}}$.

The values of $V_{2\Delta}^{\mathrm{HFe-ch}}$ obtained from the fit in the three $p_{\mathrm{T}}^{\mathrm{e}}$ intervals are $0.0038 \pm 0.0008(\mathrm{stat}) \pm 0.0006(\mathrm{syst})$, $0.0040 \pm 0.0007(\mathrm{stat}) \pm 0.0005(\mathrm{syst})$ and $0.0019 \pm 0.0019(\mathrm{stat}) \pm 0.0003(\mathrm{syst})$ for $1.5 < p_{\mathrm{T}}^{\mathrm{e}} < 2$ GeV/c, $2 < p_{\mathrm{T}}^{\mathrm{e}} < 4$ GeV/c and $4 < p_{\mathrm{T}}^{\mathrm{e}} < 6$ GeV/c, respectively. The $V_{1\Delta}^{\mathrm{HFe-ch}}$ fit values are compatible with zero in all the $p_{\mathrm{T}}^{\mathrm{e}}$ intervals. The measured $V_{2\Delta}^{\mathrm{HFe-ch}}$ is larger than zero with a significance of 4.6σ for the $2 < p_{\mathrm{T}}^{\mathrm{e}} < 4$ GeV/c range. The significance for $V_{2\Delta}^{\mathrm{HFe-ch}} > 0$ in at least one of the $p_{\mathrm{T}}^{\mathrm{e}}$ intervals, $1.5 < p_{\mathrm{T}}^{\mathrm{e}} < 2$ GeV/c and $2 < p_{\mathrm{T}}^{\mathrm{e}} < 4$ GeV/c, combining statistical and systematical uncertainties, is about 6σ.

Assuming its factorization in single-particle v_2 coefficients [8], the $V_{2\Delta}^{\mathrm{HFe-ch}}$ can be expressed as the product of the second-order Fourier coefficients of the heavy-flavour decay electron (v_2^{HFe}) and charged particle (v_2^{ch}) azimuthal distributions, hence $v_2^{\mathrm{HFe}} = V_{2\Delta}^{\mathrm{HFe-ch}}/v_2^{\mathrm{ch}}$. The v_2^{ch} value in the range $0.3 < p_{\mathrm{T}}^{\mathrm{ch}} < 2$ GeV/c was obtained from the weighted average of the values measured in smaller $p_{\mathrm{T}}^{\mathrm{ch}}$ ranges in [8], providing $v_2^{\mathrm{ch}} = 0.0460 \pm 0.0014(\mathrm{stat}) \pm 0.0046(\mathrm{syst})$. The v_2^{HFe} values are reported in Fig. 3 and compared to those measured for charged particles, dominated by light-flavour hadrons, and inclusive muons at large rapidity (in p-going and Pb-going directions), which are mostly coming from heavy-flavour hadron decays for $p_{\mathrm{T}}^{\mu} > 2$ GeV/c. The strength of the modulation is similar for heavy- and light-flavour particles, although the uncertainties are large and the p_{T} interval of electron parents (heavy-flavour hadrons) is considerably broader than the range addressed in the light-flavour hadron measurement. The comparison of v_2^{HFe} at mid-rapidity with v_2 of inclusive muons at forward and backward rapidity is not straightforward, due to the different cold nuclear matter effects affecting heavy-flavour production at different rapidities [46] and to the non-heavy-flavour contamination for muons at low p_{T}^{μ}. A comparison of v_2^{HFe} with the J/ψ results [27] is also challenging, considering the different fragmentation process of heavy quarks to open and hidden mesons, and is not presented here. The v_2^{HFe} in p–Pb collisions is found to be similar

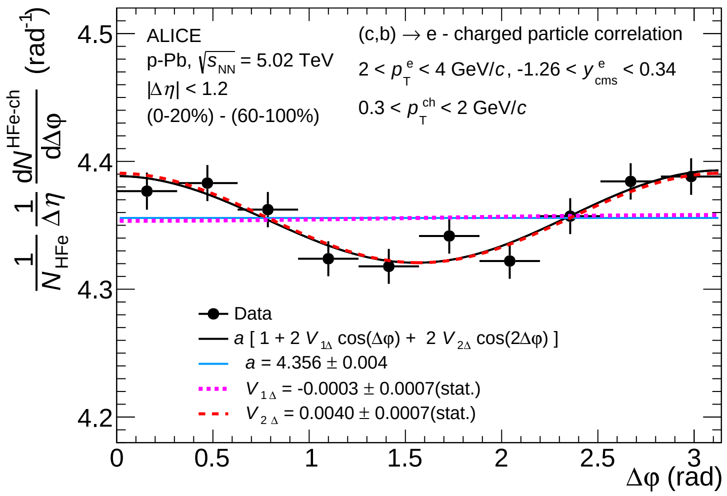

Fig. 2: Azimuthal correlation distribution between heavy-flavour decay electrons and charged particles, for high-multiplicity p–Pb collisions after subtracting the jet contribution based on low-multiplicity collisions. The distribution is shown for $2 < p_T^e < 4$ GeV/c and $0.3 < p_T^{ch} < 2$ GeV/c. The figure contains only statistical uncertainty. The best fit (Eq. 3) to the data points and its Fourier decomposition are also shown.

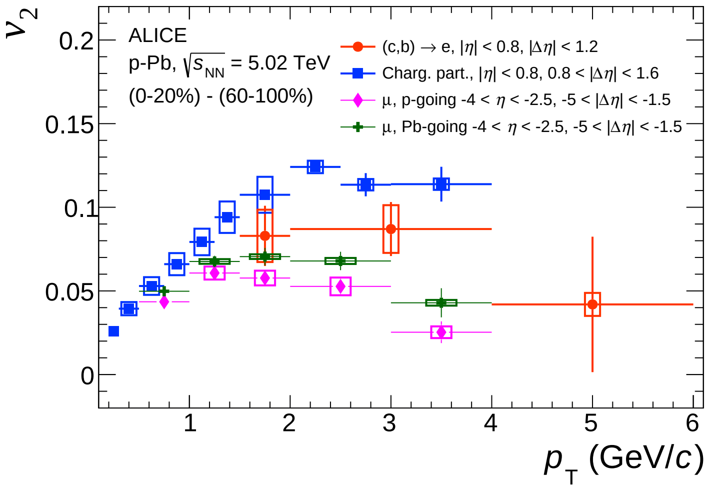

Fig. 3: Heavy-flavour decay electron v_2 as a function of transverse momentum compared to the v_2 of unidentified charged particles [8] and inclusive muons [28]. Statistical and systematic uncertainties are shown as bars and boxes, respectively.

in magnitude to the one in non-central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [25]. The significance for $v_2^{HFe} > 0$ is 5.1σ for $1.5 < p_T^e < 4$ GeV/c, which provides a very strong indication for the presence of long-range anisotropies for heavy-flavour particles also in high-multiplicity p–Pb collisions.

In summary, we report the measurement of v_2 for open heavy-flavour particles at mid-rapidity in high-multiplicity p–Pb collisions. The analysis was carried out via a Fourier decomposition of the azimuthal correlation distribution between heavy-flavour decay electrons and charged particles. After the removal of the jet contribution a $V_{2\Delta}$-like modulation was obtained in the high-multiplicity correlation distributions, similarly to what was previously observed for light-flavour di-hadron correlations. A fit to the correlation distributions was used to characterise the modulation. The heavy-flavour decay electron v_2 was found to have similar magnitude to the charged particle v_2 in the common p_T interval [5]. The measured heavy-flavour decay electron v_2 is positive with a significance of more than 5σ in the $1.5 < p_{\mathrm{T}}^{\mathrm{e}} < 4$ GeV/c range. This measurement complements previous measurements for light-flavour hadrons [5], providing new information on the behaviour of heavy-flavour hadrons to understand the azimuthal anisotropies observed in small collision systems.

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