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Elliptic flow of electrons from beauty-hadron decays in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

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Abstract

The elliptic flow of electrons from beauty hadron decays at midrapidity ($|y| < 0.8$) is measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with the ALICE detector at the LHC. The azimuthal distribution of the particles produced in the collisions can be parameterized with a Fourier expansion, in which the second harmonic coefficient represents the elliptic flow, v_2. The v_2 coefficient is measured for the first time in transverse momentum (p_{T}) range 1.3–6 GeV/c in the centrality class 30–50%. The measurement of electrons from beauty-hadron decays exploits their larger mean proper decay length $c\tau \approx 500$ μm compared to that of charm hadrons and most of the other background sources. The v_2 of electrons from beauty hadron decays at midrapidity is found to be positive with a significance of 3.75σ. The results provide insights on the degree of thermalization of beauty quarks in the medium. A model assuming full thermalization of beauty quarks is strongly disfavoured by the measurement at high p_{T}, but is in agreement with the results at low p_{T}. Transport models including substantial interactions of beauty quarks with an expanding strongly-interacting medium describe the measurement.

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[*] See Appendix A for the list of collaboration members

The main goal of the ALICE experiment [1] is the study of strongly-interacting matter at the high energy density and temperature reached in ultra-relativistic heavy-ion collisions at the Large Hadron Collider (LHC). In these collisions, the formation of a deconfined state of quarks and gluons, the quark–gluon plasma (QGP), is predicted by quantum chromodynamic (QCD) calculations on the lattice [2–6]. Because of their large masses, heavy quarks (charm (c) and beauty (b)) are mainly produced in hard scattering processes at the initial stage of the collision, before the formation of the QGP. Subsequently, they interact with the QGP, losing energy via radiative [7, 8] and collisional scattering [9–11] processes. Heavy-flavor hadrons and their decay products are thus effective probes to study the properties of the medium created in heavy-ion collisions. In non-central collisions, interactions among the medium constituents translate the initial spatial anisotropy in the coordinate space of nucleons participating in the collision into a momentum space anisotropy of produced particles in the final state [12]. The momentum anisotropies are characterized by the flow harmonic coefficients v_{n} from the Fourier expansion of the particle azimuthal distribution with respect to the symmetry plane. The dominant flow harmonic is the elliptic flow v_2 [13]. At low transverse momentum, $p_{\mathrm{T}} < 3$ GeV/c, the measurements of positive v_2 are considered a manifestation of the collective hydrodynamical expansion of the medium [14–17]. At high p_{T} ($p_{\mathrm{T}} > 3$ GeV/c), v_2 measurements give insight into the path-length dependence of the in-medium parton energy loss [18–20].

The measurements of D-meson and J/ψ v_2 in heavy-ion collisions, performed at RHIC in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV [21] and at the LHC in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV and 5.02 TeV [22–28], suggest that the interaction of charm quarks with the medium is sufficiently strong to make them thermalize and thereby take part in the collective flow of the medium [29–35]. Additional mechanisms, like coalescence and recombination of charm quark with the lighter quarks produced in the medium, can contribute to the flow of heavy-flavor particles [36]. Models that describe the flow measurements of charm quarks require that their thermalization time is of the order of the system lifetime ($\approx$ 10 fm/c) [29]. This indicates that low-p_{T} charm quarks may be fully thermalized in the QGP due to their interaction with the medium. Possibly a non-thermalized probe is required to assess the interaction with the medium more thoroughly, with the heavier beauty quarks being the natural candidate. It has been predicted by transport models that beauty quarks may experience sufficient scattering in the medium, resulting in positive v_2 values [34, 37, 38]. Measurements of the anisotropic flow of leptons from charm and beauty hadron decays also showed that heavy quarks undergo significant rescattering in the medium and thus participate in its expansion [39–42]. However, strong conclusions about the dynamics of the beauty quark can not be drawn from those measurements, and separation of the charm and beauty contribution is necessary. The measured v_2 coefficient of the non-prompt J/ψ carried out by the CMS collaboration is consistent with zero within large experimental uncertainties for $p_{\mathrm{T}} > 3$ GeV/c [43]. Recent measurements of the v_2 coefficient for Υ(1S) by ALICE [44], for $p_{\mathrm{T}} < 15$ GeV/c, are consistent both with zero and with the small value predicted by transport models [45, 46] within uncertainties. Studies based on the Blast-Wave model show that, due to the large Υ(1S) mass, even with full thermalization a sizeable elliptic flow would only be expected at $p_{\mathrm{T}} > 10$ GeV/c [47]. Hence lighter beauty hadrons, and their decay particles, would provide important additional information for the study of the interaction of beauty quarks with the medium. Recent ATLAS measurement of v_2 of muons from heavy-flavor hadron decays, including the separation between charm and beauty quarks contributions, in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV for $p_{\mathrm{T}} > 4$ GeV/c revealed smaller flow coefficients for muons from beauty hadron decays compared to those from charm hadrons [48].

In this Letter, the measurement of the v_2 of electrons (and positrons) from beauty hadron decays at midrapidity ($|y| < 0.8$) in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV recorded in 2018 with the ALICE detector is reported. The measurement is performed for the first time in the p_{T} interval $1.3 < p_{\mathrm{T}} < 6$ GeV/c. The measurement is based on 77×10^{6} minimum bias Pb–Pb collisions with a primary vertex reconstructed within ±10 cm from the detector center [49] in the 30–50% centrality interval. Two forward and backward scintillator arrays (V0A and V0C) are used to determine the collision centrality [50, 51].

Electron candidate tracks, reconstructed with up to 159 measurement points in the Time Projection Chamber (TPC) and up to 6 in the Inner Tracking System (ITS), are required to fulfill standard track selection criteria as listed in [22, 52]. To minimize the contribution of electrons from photon conversions in the detector material of the ITS and the fraction of tracks with misassociated hits, tracks are required to have associated hits in both Silicon-Pixel-Detector (SPD) layers, which constitute the two innermost layers of the ITS. This requirement removes particles produced outside the SPD from the track sample. However, in the high-multiplicity environment of heavy-ion collisions, such tracks can be misassociated with hits in the SPD layers produced by other particles. Electron identification is done using the TPC and the Time of Flight detector (TOF) [22, 52]. Electrons are identified by requiring the measured time-of-flight up to the TOF radius of 3.8 m on average to be within 3σ of the expected value for electrons and their specific energy loss $\mathrm{d}E/\mathrm{d}x$ in the TPC to be within -1σ and $+3\sigma$ with respect to the expected $\mathrm{d}E/\mathrm{d}x$ of electrons.

Electrons passing the track and identification selection criteria originate, besides from beauty-hadron decays, from Dalitz and di-electron decays of prompt light neutral mesons and charmonium states, photon conversions in the detector material, semi-leptonic decays of prompt-charm hadrons and decay chains of hadrons carrying a strange (or anti-strange) quark. Measurements of electrons from beauty-hadron decays exploit their larger average impact parameter (d_0), defined as distance of closest approach to the primary vertex in the plane transverse to the beam line, compared to that of charm hadrons and most other background sources. The sign of the impact parameter value is attributed based on the relative position of the track and the primary vertex, i.e. if the primary vertex is on the left- or right-hand side of the track with respect to the particle momentum direction in the transverse plane. The impact parameter is multiplied with the sign of the particle charge and the magnetic field configuration [52]. Electrons from photon conversions in the detector material are created at some distance from the primary vertex and in the direction of the photon. Their tracks bend away from the primary vertex, leading to an asymmetry with a mean impact parameter $d_0 < 0$. This asymmetric impact parameter distribution allows for a better separation from the other electron sources, which are mostly symmetric around 0.

The experimental estimate of the symmetry plane of the collision-geometry in the azimuthal direction, the event plane Ψ_2, is determined using the signals produced by charged particles in the eight azimuthal sectors of each V0 array. Non-uniformities in the V0 acceptance and efficiency are corrected for using the procedure described in [53].

The $v_2\{\mathrm{EP}\}$ is given by

$$v_2\{\mathrm{EP}\} = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\mathrm{in}} - N_{\mathrm{out}}}{N_{\mathrm{in}} + N_{\mathrm{out}}}, \tag{1}$$

where N_{in} and N_{out} are the number of beauty-decay electrons in two 90°-wide intervals of $\Delta\varphi = \varphi - \Psi_2$: in-plane ($-\frac{\pi}{4} < \Delta\varphi < \frac{\pi}{4}$ and $\frac{3\pi}{4} < \Delta\varphi < \frac{5\pi}{4}$) and out-of-plane ($\frac{\pi}{4} < \Delta\varphi < \frac{3\pi}{4}$ and $\frac{5\pi}{4} < \Delta\varphi < \frac{7\pi}{4}$), respectively. The resolution (R_2) of the event plane is measured with the three sub-event method [25]. The sub-events are defined according to the signals in the V0 detectors (both A and C sides) and the tracks in positive ($0 < \eta < 0.8$) and negative ($-0.8 < \eta < 0$) pseudorapidity regions of the TPC. R_2 is calculated in 1% centrality intervals and a weighted average for the 30–50% interval is obtained using the number of binary nucleonâĂŞnucleon collisions as weights [25]. The average R_2 value in the 30–50% centrality class is 0.77 [24].

The N_{in} and N_{out} yields of electrons from beauty-hadron decays are extracted by fitting the impact parameter distribution of all electron candidates in data with Monte Carlo (MC) templates for different electron sources [52]. A MC sample of minimum-bias (MB) Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, generated with HIJING v1.36 [54], is used to obtain the impact parameter distributions of photon conversions and Dalitz decays. To increase the sample of electrons from charm- and beauty-hadron decays, a sample of charm and beauty quarks generated with PYTHIA6 [55] is embedded into each Hijing MC event. The generated particles are propagated through the ALICE apparatus using GEANT3 [56]. Four classes of electron sources are used: electrons from beauty-hadron decays, from charm-hadron decays, from photon conversions, and electrons from other processes, dominated by Dalitz decays of light neutral mesons. As these decays happen essentially at the interaction vertex, the measured impact parameter distribution of these tracks represents the p_T-dependent impact parameter resolution. Similarly, the remaining hadron contamination mostly consists of hadrons produced close to the primary vertex, making its impact parameter distribution similar to that of the Dalitz electrons. The slight difference in the distributions for Dalitz electrons and hadrons results in an uncertainty of 0.009 on the final v_2 in the first p_T interval, falling quickly with p_T. The yield of strange-hadron decays is small compared to other background sources. The corresponding contribution is considered as part of the Dalitz electron template. Due to the long lifetime, this contribution has a much wider impact parameter distribution and is therefore largely reduced by the applied d_0 range of [-0.1, 0.1] cm in the fitting procedure [52].

The template fits are based on the method proposed in [57] and implemented as in [52]. Detailed corrections to the MC templates, listed and described below, are applied in order to take into account effects not simulated in MC. Special care is taken to assess differences in the in-plane and out-of-plane templates as the effects of the corrections do not cancel in the computation of the v_2. The main corrections applied in the MC are: i) resolution of the d_0 distribution, ii) misassociated electrons from photon conversions and their multiplicity dependence, iii) p_T distribution of charm and beauty hadrons in-plane and out-of-plane and iv) baryon-to-meson ratio of charm and beauty hadrons.

To ensure angular isotropy of the d_0 reconstruction in data, the mean d_0 of primary particles is compared in different regions in azimuth, z-position and p_T with a granularity smaller than the detector components and then recentered. Depending on p_T, the d_0 resolution in the MC simulations is about 11–13% better than in data [58, 59]. Primary pions and kaons are used for the comparison. It is observed that the resolution of the impact parameter does not depend significantly on the local track density.

The correct template shape of electrons from photon conversions depends on the production vertex and on the track multiplicity. In-plane and out-of-plane events have different local track densities, requiring separate corrections for the respective templates. This is achieved by choosing different centrality ranges for each template in the simulations. The ranges are defined based on how well they describe either the in-plane or out-of-plane reconstruction efficiencies of pions from K^0_S decays, as the production vertex of these decays is more accurately reconstructed. The systematic uncertainties are estimated by varying the nominal centrality classes in the simulations and are estimated to be 0.006 at low p_T and decreases to 0.001 with increasing p_T.

Because electrons from heavy-flavor hadron decays at a given momentum may originate from decaying particles over a broader momentum range, their d_0 distributions depend on the p_T distributions of these decaying particles. Hence it is necessary to correct for the difference in the p_T distribution of particles that decay to electrons between data and MC. For the charm case, this can be done by making use of the measured charm mesons p_T spectral shape and v_2 at the same collision energy [26, 60]. From these measurements, separate p_T distributions and thus corrections are used for the in-plane and out-of-plane templates. To assess the uncertainty, the result is compared to a case where the assumed D meson v_2 is halved. An absolute systematic uncertainty of 0.004 is assigned from this comparison.

As there is no available measurement of the low-p_T beauty hadron elliptic flow, the corrections for the beauty template are based on FONLL calculation [61] multiplied with the p_T-dependent corrections due to the nuclear modification factor (R_{AA}) and the v_2 to take into account beauty suppression and possible anisotropy. The upper limit of the estimated R_{AA} value is the case of no suppression, $R_{AA} = 1$, while the lower limit is obtained by interpolating the TAMU prediction [38], which is consistent with measurements of $R_{AA} \approx 0.4$ at high p_T [52]. The arithmetic mean of the two cases is used for the central values of the measurement, with the two limits used to estimate the systematic uncertainty. An absolute systematic variation of 0.0023 at low $p_{\rm T}$ and of 0.011 at high $p_{\rm T}$ is found and assigned as an uncertainty. A significant effect arises from the modification of the $p_{\rm T}$ spectra due to beauty-hadron v_2 since it gives a different correction for the in-plane and out-of-plane templates. For the central value of the measurement, the assumption of $v_2 = 0.014\times p_{\rm T}^2\, e^{(-1/3\times p_{\rm T})}$ (with $p_{\rm T}$ in units of GeV/c) is chosen as a generic function inspired by the prediction of the TAMU model [38]. The systematic uncertainty is evaluated by varying the v_2 value from zero to two times as large, the latter giving a peak of 0.14. For these variations, the change in the measured beauty hadron decay electron v_2 is much smaller than the variation of the assumed hadron v_2. This gives a flat systematic uncertainty of 0.006 up to $p_{\rm T}$ = 4 GeV/c and of 0.012 in the last $p_{\rm T}$ interval.

Differences in the lifetimes of the various charm and beauty hadrons cause variations in the associated impact parameter distributions of its decay electrons. For charm, the largest difference is in the decays of the baryons with respect to the mesons, while for beauty the lifetime of mesons and baryons are very similar and the effect of their different fractions in MC compared to data is negligible. For the charm case, a $p_{\rm T}$ dependent correction is performed for the $\Lambda_{\rm c}/{\rm D}^0$ fraction similar to model predictions [62–64], which describe experimental measurements [65, 66, 66, 67]. This is compared to a $p_{\rm T}$-independent correction, that increases the $\Lambda_{\rm c}/{\rm D}^0$ by a factor of 3, which gives no difference due to the effects cancelling out in the computation of the v_2.

Multiplicity dependence of the efficiency in the particle identification with the TOF detector is evaluated, and it is found to be within 0.5%, which is propagated to an uncertainty of 0.0014 on the v_2. No multiplicity dependence is found for the efficiency of particle identification with the TPC.

Figure 1 shows examples of the resulting fits in-plane (left panel) and out-of-plane (right panel) of electrons d_0 distributions for the interval $2.5 < p_{\rm T} < 3$ GeV/c. In the figure the MC templates are corrected for all effects described above.

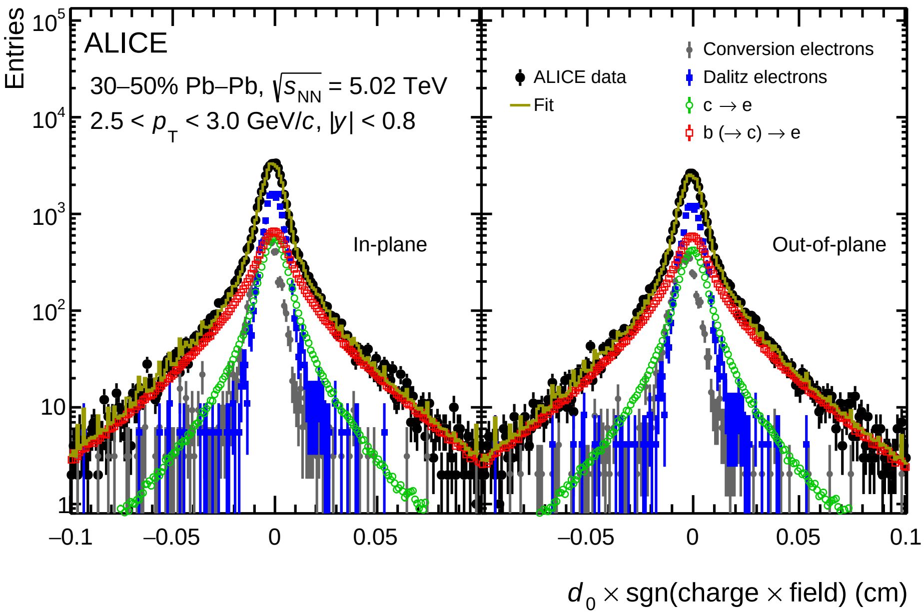

Figure 1: Examples of the electron transverse impact parameter fits in-plane (left) and out-of-plane (right) for $2.5 < p_{\rm T} < 3$ GeV/c. Distributions from data and the four MC templates, electrons from beauty (b (→ c) → e) and charm (c → e) hadron decays, electrons from photon conversions (Conversion electrons) and from other sources (Dalitz electrons) used in the fit are shown.

Figure 2 shows the v_2 of electrons from beauty hadron decays at midrapidity ($|y| < 0.8$) as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 30–50% centrality interval. A positive v_2 with a significance of 3.75σ is observed for the first time in this low p_T range (1.3–6 GeV/c) using the average deviation to positive v_2 divided by the uncertainty as a test statistic. The systematic uncertainties are assumed to be fully correlated for this purpose. No significant p_T dependence of the v_2 is observed.

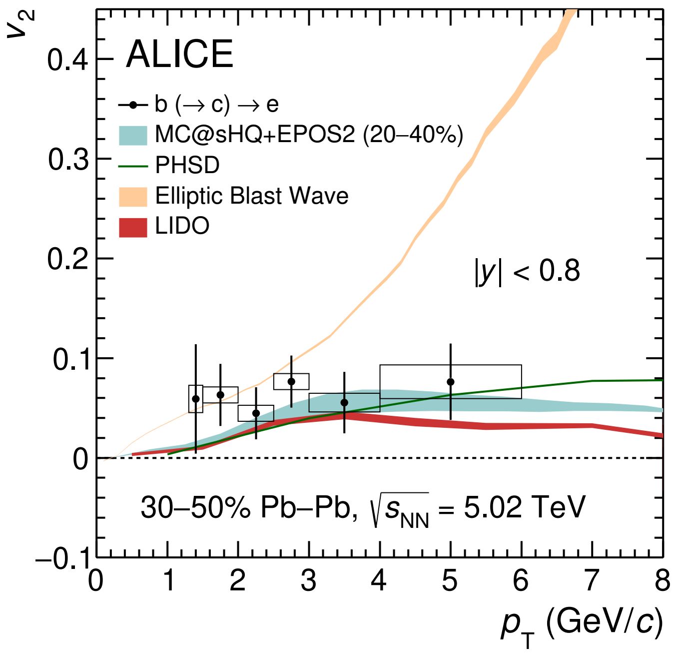

Figure 2: Elliptic flow of electrons from beauty hadron decays in the 30–50% centrality class in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at midrapidity as function of p_T compared with model calculations [30–32, 68].

The measured v_2 of beauty decay electrons is compared with the predictions from several transport models which include significant interaction of beauty quarks with a hydrodynamically-expanding QGP [30–32, 68]. These models are observed to well describe the D meson anisotropy and suppression in heavy-ion collisions at the LHC [23–27, 69–71]. The MC@sHQ+EPOS [30] is a perturbative QCD model which includes radiative and collisional energy loss. The uncertainties of the model calculations are evaluated considering pure elastic and radiative energy losses, including also different scattering rates and different rescaling factors. Modification of nuclear parton distribution functions, like shadowing, is not considered for b quarks. The LIDO model [32, 68] also includes both radiative and collisional energy loss. This model uses experimental data to calibrate a Langevin-based transport model and thus extract the transport coefficients directly from data via a Bayesian analysis. In the case of LIDO, the reported model uncertainties are purely statistical. Within this model, the v_2 for beauty hadrons is much smaller than for charm hadrons. The PHSD model [31] is a microscopic off-shell transport model based on a Boltzmann approach which includes only collisional energy loss. Initial-state event-by-event fluctuations are included in all transport models described here. Even though the models differ in several aspects related to the interactions both in the QGP and in the hadronic phase as well as to the medium expansion, they all provide a fair description of the measurement. Similar agreement of these models was previously observed when compared to the R_{AA} of electrons from beauty-hadron decays [52]. With the current experimental uncertainties, no model is clearly favoured or disfavoured. A model calculation based on an extension of the blast-wave model [47] is also compared with the measurement. The calculation shown is based on B^0 mesons, and the PYTHIA8 decayer is used for their decays into electrons [72]. Assuming full thermalization, this model predicts a v_2 of $\Upsilon(1S)$ close to zero in the range measured by ALICE, which is consistent with the measurement. The results for beauty hadron decay electrons give a much larger v_2 due to mass ordering effect. Thus, in this case the comparison is suitable to assess the degree of thermalization of beauty quarks at low $p_{\rm T}$. The error band represents purely statistical uncertainty. This simple model is qualitatively in agreement with the measurement within the uncertainties for $p_{\rm T} < 3$ GeV/c, while it significantly diverges from the data at higher $p_{\rm T}$. Within this model, the v_2 in the measured $p_{\rm T}$ range mainly comes from beauty hadrons below $p_{\rm T}$ = 10 GeV/c, suggesting that beauty quarks may not fully thermalize in this $p_{\rm T}$ interval.

In summary, the measurement of the elliptic flow of electrons originating from beauty hadron decays at midrapidity in semicentral Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV is presented for the first time in this low $p_{\rm T}$ interval 1.3–6 GeV/c. The measurement is crucial for the understanding of the degree of thermalization of beauty quarks in the QGP. The v_2 of electrons from beauty hadron decays is found to be positive with a significance of 3.75σ. Comparison with models suggests that beauty quarks may not fully thermalize in the medium and the measurement is consistent with a lower beauty v_2 than observed for charm. The measurement provides new insights and constraints to theoretical models of beauty quark interactions in the QGP.

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