Charm and beauty isolation from heavy flavor decay electrons in p+p and Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV at LHC

Dongsheng Li\textsuperscript{a}, Fan Si\textsuperscript{a}, Yidan Zhao\textsuperscript{a}, Pengyu Zhou\textsuperscript{a}, Yifei Zhang\textsuperscript{a,\dagger}, Xiujun Li\textsuperscript{a} and Chengxi Yang\textsuperscript{a}

\textsuperscript{a}State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China

\begin{abstract}
We present an analysis on the heavy flavor hadron decay electrons with charm and beauty contributions decomposed via a data driven method in p+p and Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV at LHC. The transverse momentum $p_T$ spectra, nuclear modification factor $R_{AA}$ and azimuthal anisotropic flow $v_2$ distributions of electrons from charm and beauty decays are obtained. We find that the electron $R_{AA}$ from charm ($R^{c+\ell}_AA$) and beauty ($R^{b+\ell}_AA$) decays are suppressed at $p_T > 2.0$ GeV/c in Pb+Pb collisions, which indicates that charm and beauty interact with and lose their energy in the hot-dense medium.

A less suppression of $R^{c+\ell}_AA$ than $R^{b+\ell}_AA$ at $2.0 < p_T < 8.0$ GeV/c is observed, which is consistent with the mass-dependent partonic energy loss scenario. A non-zero electron $v_2$ from beauty decays ($v_2^{b+\ell}$) is observed and in good agreement with ALICE measurement. At low $p_T$ from 1.0 to 3.0 GeV/c, a discrepancy between RHIC and LHC results is observed with an 85% confidence level, which might be a possible hint of an energy-dependent behavior of beauty quarks reacting with the medium created in heavy-ion collisions. At 3.0 $< p_T < 7.0$ GeV/c, $v_2^{b+\ell}$ deviates from a number-of-constituent-quark (NCQ) scaling hypothesis, which favors that beauty quark is unlikely thermalized in heavy-ion collisions at LHC energy.

\end{abstract}

1. Introduction

Strong interactions among quarks and gluons by exchanging color charges are described by the theory of Quantum Chromodynamics (QCD). Quarks and gluons are confined in color-neutral hadrons and can be liberated under an extremely hot and dense condition such as the stage of a few microseconds after the big bang of the universe. Ultra-relativistic heavy-ion collisions provide such environment to create the state of matter known as quark-gluon plasma (QGP) that behaves almost as a perfect fluid [1, 2, 3]. Heavy quarks (charm and beauty) are produced mainly via initial hard scatterings in heavy-ion collisions due to their large masses. Their production yield can be evaluated by perturbative QCD. Thus, heavy quarks are believed to experience the whole medium dynamic evolution after their creation and maintain conserved quark numbers. Therefore, heavy quarks are an ideal probe to study QGP matter and sensitive to its thermal dynamic properties [4, 5, 6]. In the past ten years, open heavy flavor hadrons have been measured in many experiments at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) [7, 8, 9, 10]. It was found that the nuclear modification factors ($R_{AA}$) of both electrons from heavy flavor decays and open charm mesons were strongly suppressed at high transverse momentum ($p_T$) in central heavy-ion collisions. This indicates that charm quarks significantly lose their energy when traversing the hot-dense medium. A significant elliptic flow ($v_2$) of open charm mesons is also observed and comparable with light flavor hadrons, which indicates that charm quark reaches thermalization in heavy-ion collisions.

Beauty, with a factor of three larger mass than charm, is predicted to lose less energy than charm in the medium created in heavy-ion collisions either with a suppression of the gluon radiation angle [11, 12, 13] or the elastic collisions [4, 14]. And its $v_2$ is probably different from those of charm quark and light flavors if it is far from thermalization. However, measurement of beauty is challenging due to its small production yields [14]. From its decay daughters are less suppressed compared to those of prompt open charm mesons at $p_T$ up to $\sim 20$ GeV/c, which is consistent with the mass hierarchy of the parton energy loss in the medium [15, 16, 17, 18, 19, 20, 21, 22]. Recently, a sizable electron $v_2$ from beauty decays was also measured by ALICE [23], which indicates strong interactions between beauty and the medium. Since charm looks no significant difference compared with light quarks in terms of $R_{AA}$ and $v_2$ in RHIC and LHC energies [5, 24], it is crucial to study whether beauty is sensitive to the different media created at RHIC and LHC energies and behaves differently under different temperatures.

In a previous study, the charm and beauty contributions are separated from the inclusive heavy flavor electrons (HFE) in 200 GeV Au+Au collisions at RHIC [25]. It was found that the electron $R_{AA}$ from beauty decays is less suppressed compared to that from charm decays, which is consistent with the mass-dependent energy loss expectation. And a first zero electron $v_2$ from beauty decays, lower than a number-of-constituent-quark (NCQ) scaling hypothesis, was observed at low $p_T$, which indicates that beauty quark is unlikely thermalized and too heavy to be moved following
the collective flow of lighter partons in heavy-ion collisions at RHIC energy.

In this paper, we perform an analysis in a similar way to separate charm and beauty contributions from heavy flavor decay electrons in 5.02 TeV p+p and Pb+Pb collisions. The $R_{AA}$ and $v_2$ of electrons from charm and beauty decays in 5.02 TeV Pb+Pb collisions at LHC are obtained and compared with those in 200 GeV Au+Au collisions at RHIC.

2. Analysis Technique and Results

2.1. Transverse Momentum Spectra and $R_{AA}$

We adopt the data-driven method developed in Ref. [25] to separate charm and beauty decay contributions from the inclusive HFE spectra [26] in 0–10% and 30–50% central Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV and p+p collisions at $\sqrt{s} = 5.02$ TeV at LHC by taking advantage of the most recent charm hadron measurements. Different from the previous study at RHIC energy, the HFE measurement [26] from the ALICE experiment was not subtracted by the $J/\psi$ contribution (about 5% at $2 < p_T < 3$ GeV/c and much lower in other $p_T$ regions), and thus the $J/\psi \rightarrow e^+e^-$ contribution is also studied in this work. In Pb+Pb collisions, the ALICE experiment has precisely measured the $p_T$ spectra of prompt $D^0$, $D^\pm$ and $D_s$ mesons ($0 < p_T < 50$ GeV/c) and $\Lambda_c$ baryons ($0 < p_T < 24$ GeV/c) including their antiparticles at mid-rapidity ($|y| < 0.5$) at 0–10% and 30–50% centrality classes [27, 28, 29]. The $J/\psi$ spectra ($|y| < 0.9$) in both centrality classes are provided by the TAMU model predictions [30, 31, 32] combined with the measurement by the CMS experiment [20] at $6.5 < p_T < 50$ GeV/c, which is scaled from 0–100% centrality with the average number of binary nucleon-nucleon collisions ($\langle N_{coll} \rangle$) [33]. All the spectra are then parameterized with a Levy [34] function, and the uncertainties are given by a quadratic sum of two components: (a) 1-$\sigma$ band from the parameterization with statistical uncertainties and (b) systematic uncertainties from the parameterized spectra scaled to upper and lower limits. The parameterization at 30–50% centrality is shown as an example in Fig. 1, which works well compared with the experimental data (black points) and the TAMU prediction (black band). In p+p collisions, the prompt D-mesons ($|y| < 0.5$) [35], $\Lambda_c$ ($|y| < 0.5$) [36] and $J/\psi$ ($|y| < 0.9$) [37] spectra measured by ALICE are parameterized with the same steps as those in Pb+Pb collisions. To extend the $p_T$ ranges, the measurements of $J/\psi$ by the ATLAS experiment [38] at $12 < p_T < 40$ GeV/c and $\Lambda_c$ by CMS [39] at $10 < p_T < 20$ GeV/c are combined with the ALICE measurements for parameterization.

The charmed hadrons described above are then simulated to decay to electrons via semileptonic decay ($e^+e^-$ for $J/\psi$) channels with their parameterized $p_T$ spectra at $0 < p_T < 20$ GeV/c and Gaussian rapidity distributions ($\mu = 0$ and $\sigma = 1.7$ for open charm hadrons, $\mu = 0$ and $\sigma = 1.9$ for $J/\psi$) as inputs. These rapidity distributions have been checked by the PYTHIA [42] event generator. By varying the rapidity distributions with a sigma of $1.7 \pm 0.3$, the obtained electron spectra changes $< 1\%$ in $0 < p_T < 20$ GeV/c. The open charm hadron decays are conducted with the help of decay formfactors in the hadron rest frame which are sampled from the measured distribution by the CLEO experiment [43], while the $J/\psi$ decays are simulated with PYTHIA. Note that a non-zero $J/\psi$ polarization could have impact on the decay kinematics. Recently the ALICE experiment measured $J/\psi$ polarization which shows some hint of non-zero polarization but with large uncertainties [44]. Thus here the effect of potential $J/\psi$ polarization on the decay electron spectra is not taken into account. Figure 2 shows the electron spectra from $D^0$ (blue dashed curve), $D^\pm$ (brown dot-dot-dashed curve), $D_s$ (green dot-dashed curve), $\Lambda_c$ (cyan long-dot-dashed curve) and $J/\psi$ (violet dot-dot-dot-dashed curve) decays and the summed charm contributions ($c \rightarrow e$, black solid curve) at mid-rapidity ($|y| < 0.8$ at $p_T < 3$ GeV/c and $|y| < 0.6$ at $p_T > 3$ GeV/c) in 5.02 TeV 0–10% and 30–50% central Pb+Pb collisions and p+p collisions. All components of the total $c \rightarrow e$ production from individual charmed hadron decays are summarized in Table 1. The maximum $p_T$ of charmed hadron measurements and the contributions of unsimulated regions of charmed hadron decays ($p_T^{charm} > 20$ GeV/c) to the electrons in 0–8 GeV/c are summarized in Table 2. The contributions are found to be less than 0.04% to insure that most electrons in the region of interest come from the simulated region of charmed hadrons. The uncertainties of the charmed hadron
Table 1
Production components of the $c \rightarrow e$ spectra (0–8 GeV/c) from individual charmed hadron decays.

| centrality | 0–10% | 30–50% | p+p |
|------------|-------|--------|-----|
| $D^0 \rightarrow e$ | 25.7%–34.3% | 24.0%–33.6% | 36.8%–39.0% |
| $D^\pm \rightarrow e$ | 35.7%–58.3% | 39.2%–56.4% | 39.7%–43.0% |
| $\Lambda_c \rightarrow e$ | 6.7%–12.9% | 7.2%–10.5% | 6.3%–9.0% |
| $J/\psi \rightarrow e$ | 3.5%–10.1% | 4.3%–9.4% | 2.4%–14.2% |

Table 2
Contributions of unsimulated regions of charmed hadron decays ($p_T^{charm} > 20$ GeV/c) to the electrons in 0–8 GeV/c.

| centrality | measured $p_T^{charm}$ max (GeV/c) | contribution |
|------------|-------------------------------|--------------|
| 0–10% | 30–50% | p+p | 0–10% | 30–50% | p+p |
| $D^0 \rightarrow e$ | 50 | 35 | 35 | 0.005% | 0.015% | 0.026% |
| $D^\pm \rightarrow e$ | 50 | 35 | 35 | 0.004% | 0.012% | 0.024% |
| $\Lambda_c \rightarrow e$ | 24 | 24 | 20 | < 10^{-5} | 0.004% | 0.002% |
| $J/\psi \rightarrow e$ | 50 | 50 | 40 | < 10^{-5} | 0.006% | 0.011% |

$p_T$ inputs are propagated into the decay electron spectra, and the uncertainties of branching ratios [45] are also taken into account. The total uncertainties of electron spectra from individual charmed hadron decays are shown as shaded bands in Fig. 2. All contributions of the total uncertainties of $c \rightarrow e$ within $0 < p_T < 8$ GeV/c are summarized in Table 3. The total uncertainties of $c \rightarrow e$, quadratically summed from all uncorrelated components, are 8.0%–40.6% and 6.4%–17.9% at 0–10% and 30–50% centrality classes in Pb+Pb collisions, and 4.2%–8.2% in p+p collisions, respectively. The electron spectra from beauty hadron decays (b → e, red solid circles), are then calculated by subtracting the $c \rightarrow e$ contribution from the inclusive HFE spectra (open black squares) [26]. Figure 3 presents the $b \rightarrow e$ spectra in 0–10% (black solid squares) and 30–50% (red solid circles) central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in p+p collisions at $\sqrt{s} = 5.02$ TeV with the previously obtained result (blue open squares) [25] in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and the FONLL prediction (green open crosses) [46] at $\sqrt{s} = 5.02$ TeV shown for comparison. The p+p result obtained in this work is consistent with FONLL upper limit. And note that the $p_T$-differential yield spectra in p+p collisions is obtained by dividing the $p_T$-differential cross section spectra in Fig. 3 by the minimum bias trigger cross section $(50.9 \pm 0.9$ mb) at $\sqrt{s} = 5.02$ TeV. In all of the following uncertainty calculations, statistical and systematic uncertainties are quadratically summed into total uncertainties, unless otherwise specified.

The beauty contribution fraction in Pb+Pb and in p+p collisions ($f_{b-Pb}$ and $f_{b-p+p}$), shown as solid squares (0–10%), solid circles (30–50%) and open circles (p+p) in Fig. 4, is calculated by taking the ratio of the $b \rightarrow e$ and inclusive HFE spectra, and the $J/\psi$ contribution is not removed from the denominator (i.e., the inclusive HFE spectra). The relative uncertainty ($\delta$) of $f_{b-Pb}$ (5.0%–55.7% for $0$–10% and 6.2%–51.4% for 30–50%) and $f_{b-p+p}$ (5.6%–11.9%) is propagated from those of the $c \rightarrow e$ and the inclusive HFE spectra with

$$\delta^2 f_{b} = f_{c}^2 (\delta^2_{c-e} + \delta^2_{HFE}),$$

where $f_{c-b} = (1 - f_{b-e})/f_{b-e}$ in Pb+Pb or p+p collisions. Here we compare the results in 0–10% and 30–50% central Pb+Pb collisions, p+p collisions, the previous work in minimum bias Au+Au collisions [25] and the FONLL prediction [46]. The FONLL prediction of the beauty contribution fraction roughly match the p+p results of this work at $\sqrt{s} = \ldots$
Charm and beauty isolation from heavy flavor decay electrons in p+p and Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at LHC

Table 3
Uncertainty components of the $c \rightarrow e$ spectra (0–8 GeV/c) from electron spectra from individual charmed hadron decays.

| Centrality | 0–10% | 30–50% | p+p | 0–10% | 30–50% | p+p | 0–10% | 30–50% | p+p |
|------------|-------|--------|-----|-------|--------|-----|-------|--------|-----|
| $\delta f(D^{+} \rightarrow c)$ | 3.5%–7.6% | 2.6%–6.1% | 1.8%–4.3% | 0.4%–0.6% | 0.4%–0.6% | 0.1%–0.3% | 0.5%–0.7% | 0.4%–0.7% | $\times$ |
| $\delta f(D^{±} \rightarrow c)$ | 5.2%–39.8% | 4.0%–15.7% | 1.7%–4.2% | 0.6%–1.1% | 0.7%–1.1% | 0.7%–0.9% | 0.7%–1.2% | 0.7%–1.2% | $\times$ |
| $\delta f(D^{-} \rightarrow c)$ | 1.1%–4.8% | 1.0%–3.1% | 0.6%–1.9% | 0.4%–0.8% | 0.4%–0.7% | 0.3%–0.6% | 0.1%–0.3% | 0.1%–0.3% | $\times$ |
| $\delta f(\Lambda \rightarrow c)$ | 0.8%–2.6% | 1.0%–2.8% | 0.3%–2.1% | 1.3%–3.8% | 1.6%–3.6% | 0.9%–5.4% | $\times$ | $\times$ | $\times$ |

$\delta (J/\psi \rightarrow c) < 2.4%$ | $< 1.8%$ | $< 0.9%$ | $< 0.1%$ | $< 0.1%$ | $\times$ | $\times$ | $\times$ |

5.02 TeV. The beauty contributions at both centrality classes in Pb+Pb collisions monotonically increase with $p_T$ and are significantly higher than that in p+p collisions at $p_T > 4$ GeV/c. At $p_T < 4$ GeV/c, however, similar conclusion is still tenable only in 0–10% Pb+Pb collisions, since the beauty contribution fractions in p+p collisions are comparable with those in 30–50% Pb+Pb collisions. At first, for $p_T < 2$ GeV/c, the beauty contributions are smaller than charm, then at $p_T \geq 3$ GeV/c, they overwhelm the charm and start to be flattened, and finally at $p_T \sim 7$ GeV/c, the beauty contributions reach a level of 70%. It is also observed that the result at 0–10% centrality are slightly higher than that at 30–50%, and that the results at Pb+Pb 5.02 TeV show slightly lower than that at Au+Au 200 GeV at $p_T > 4$ GeV/c. This could be due to more energy loss of beauty quark at higher collision energy. However, considering the large uncertainties, the difference is not significant.

The $R_{AA}$ of electrons from individual charm and beauty hadron decays ($R_{c\rightarrow e}^{AA}$ and $R_{b\rightarrow e}^{AA}$) are extracted with the formulae [25]

\[
R_{c\rightarrow e}^{AA} = \frac{f_{b-Pb}^{b\rightarrow e}R_{inc}^{b\rightarrow e}}{f_{pp}^{b-Pb}R_{inc}^{c\rightarrow e}}.
\]

(2)

Figure 3: Electron spectra from beauty hadron decays in 0–10% and 30–50% central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, p+p collisions at $\sqrt{s} = 5.02$ TeV compared with the FONLL prediction [46] and the result in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [25].

Figure 4: Beauty hadron decay electron fractions ($f_{b\rightarrow e}$) at $\sqrt{s_{NN}} = 5.02$ TeV in 0–10% and 30–50% central Pb+Pb collisions ($|\eta| < 0.8$ at $p_T < 3$ GeV/c and $|\eta| < 0.6$ at $p_T > 3$ GeV/c) and at $\sqrt{s} = 5.02$ TeV in p+p collisions ($|\eta| < 0.8$) compared with those by FONLL calculations [46] and in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV ($|\eta| < 0.7$) [25].

\[ R_{AA}^{b\rightarrow e} = \frac{f_{Pb-Pb}^{b\rightarrow e}}{f_{pp}^{b-Pb}} R_{inc}^{b\rightarrow e}, \]

(3)

where the $R_{inc}^{b\rightarrow e}$ represents the $R_{AA}$ of inclusive electrons from heavy flavor hadron decays ($|\eta| < 0.8$ at $p_T < 3$ GeV/c and $|\eta| < 0.6$ at $p_T > 3$ GeV/c) measured by ALICE [26]. Figure 5 shows the $R_{c\rightarrow e}^{AA}$ and $R_{b\rightarrow e}^{AA}$ at 0–10% (blue solid squares and black solid circles) and 30–50% (green open squares and violet open circles) centrality classes as functions of $p_T$ extracted from Eqs. (2) and (3). The results of $R_{b\rightarrow e}^{AA}$ are consistent with the ALICE preliminary measurements [47] using a different impact parameter method shown as red and orange solid stars at both centrality classes. At each centrality class, clear suppression is observed for both $R_{AA}^{c\rightarrow e}$ and $R_{AA}^{b\rightarrow e}$ at $p_T > 2.0$ GeV/c, which indicates that charm and beauty quarks strongly interact with the hot dense medium and lose energy. Meanwhile, $R_{AA}^{b\rightarrow e}$ is less suppressed compared with $R_{AA}^{c\rightarrow e}$ at $p_T > 2.0$ GeV/c, which is consistent with the mass-dependent energy loss prediction. The $R_{AA}^{c\rightarrow e}$ at 30–50% centrality is observed to be higher than that at 0–10% at $p_T > 2.0$ GeV/c and a similar centrality dependence can be observed for $R_{AA}^{b\rightarrow e}$ at $p_T > 4.5$ GeV/c, which suggests that heavy quarks lose more energy in the
interaction with the medium created in more central collisions, as seen in Fig. 5. Theoretical model predictions with the TAMU model [48, 49, 50] and Parton-Hadron-String Dynamics (PHSD) [51] are also shown for comparison. TAMU model calculations agree with the $R_{AA}^{0-10}\%$ results but seem to overestimate $R_{AA}^{30-50}\%$ better but underestimate $R_{AA}^{50-90}\%$ for both centrality classes.

2.2. Elliptic Flow $v_2$

Similar procedures to Ref. [25] are applied to extract the $v_2$ of $c\rightarrow e$ and $b\rightarrow e$ and their uncertainties:

The latest measurement of prompt D-meson $v_2$ in 30–50% central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by ALICE [52] is parameterized from $p_T = 0$ to 24.0 GeV/c with

$$v_2 = \frac{\rho_A - \rho_{AA}}{1 + \exp\left(\frac{p_T - m_0}{p_{1/2}}\right)}\frac{\rho_T}{1 + \exp\left(\frac{p_T - m_0}{p_{1/2}}\right)} + \rho_2 (m_T - m_0),$$

where $m_T = \sqrt{p_T^2 + m_0^2}$ and $m_0$ denote the transverse and rest masses of the particle, respectively, $n$ is the number of constituent quarks and $p_i$ ($i = 0, 1, 2, 3$) are free parameters. Meanwhile, the $v_2$ of $\Lambda_c$ ($n = 3$) is also obtained from Eq. (6) by assuming that it follows the NCQ scaling as D-mesons ($n = 2$).

The azimuthal angle ($\phi$) distributions of D-mesons and $\Lambda_c$ in each $p_T$ bin is sampled according to the input $v_2$ with

$$\frac{dN}{d\phi} = 1 + 2v_2\cos(2\phi).$$

Then, semileptonic decay simulations are performed with the $p_T$ spectra and $\phi$ distributions of D-mesons and $\Lambda_c$ as inputs. The output $\phi$ distributions of decay electrons are fitted by Eq. (7) in each $p_T$ bin, and the $v_2$ of $D \rightarrow e (v_2^{D,e})$ and $\Lambda_c \rightarrow e (v_2^{\Lambda_c,e})$ can be obtained. However, different from the previous work, $J/\psi$ also exhibits a finite $v_2$ at LHC energy, so the $J/\psi$ contributions (more than 10% at $3.0 < p_T < 4.6$ GeV/c according to the following calculation) should also be considered. The latest measurement on $J/\psi$ $v_2$ only covers the 20–40% centrality at $\sqrt{s_{NN}} = 5.02$ TeV [53] and gives poor precision at mid-rapidity ($|y| < 0.9$), so the theoretical prediction mentioned in Ref. [53] is applied instead as an estimation [32, 54]. Then the $v_2$ of $J/\psi \rightarrow e (v_2^{J/\psi,e})$ is obtained in the same way mentioned above.

The $v_2$ of $c\rightarrow e (v_2^{c,e})$ and $b\rightarrow e (v_2^{b,e})$ are calculated with

$$v_2^{c,e} = u_D^{D,e} v_2^{D,e} + u_{\Lambda_c}^{\Lambda_c,e} v_2^{\Lambda_c,e} + u_{J/\psi}^{J/\psi,e} v_2^{J/\psi,e},$$

$$v_2^{b,e} = \frac{\nu_{incc} + f_{b,e}^{b,e}}{f_{b,e}^{b,e}}.$$

From Eqs. (2) and (3), the relative uncertainties of $R_{AA}^{0-10}\%$ and $R_{AA}^{50-90}\%$ can be calculated by

$$\delta^2_{R_{AA}^{0-10}\%} = \delta^2_{f_{bc}^{b,e}} + \delta^2_{f_{pb}^{b,e}} + \delta^2_{f_{pp}^{b,e}} + \delta^2_{f_{pp}^{b,e}} + \delta^2_{R_{AA}^{0-10}\%},$$

$$\delta^2_{R_{AA}^{30-50}\%} = \delta^2_{f_{pb}^{b,e}} + \delta^2_{f_{pp}^{b,e}} + \delta^2_{f_{pp}^{b,e}} + \delta^2_{R_{AA}^{30-50}\%}.$$
between the $v_2^{\text{ince}}$ measurements at both centrality classes and collision energies, so they are combined together to help perform a better fit and extrapolation.

The statistical and systematic uncertainties of measured D-meson $v_2$ are quadratically summed and propagated into the uncertainties of $v_2^{D-e}$ and $v_2^{\Lambda-c-e}$ through the decay simulations, and they are correlated as a result. The absolute uncertainties ($\sigma$) of $v_2^{\text{ince}}$ and $v_2^{b-e}$ are calculated with

$$
\sigma_{v_2^{\text{ince}}} = \left( w_{D-e} \sigma_{v_2^{D-e}} + w_{\Lambda-c-e} \sigma_{v_2^{\Lambda-c-e}} \right)^2 + u_{J/\psi} \sigma_{v_2^{J/\psi}}^2 
$$

and

$$
\sigma_{v_2^{b-e}} = f_{cb} \sigma_{v_2^{\text{ince}}}^2 + f_{cb} \sigma_{v_2^{b-e}}^2 + f_{cb} \left( v_2^{\text{ince}} - v_2^{b-e} \right)^2 \sigma_{v_2^{\text{ince}}}^2 
$$

where $\Delta v_2[A, B] = v_2^{A-e} - v_2^{B-e}$, and

In Fig. 6(b), we compare the results of $v_2^{\text{ince}}$ and $v_2^{b-e}$ in this work with those by theoretical predictions. The red dashed curve with an uncertainty band represents the $v_2^{b-e}$ assuming that B-meson $v_2$ follows the NCQ scaling with the same technique as the $v_2^{D-e}$ calculation and the decay form-factor in the B-meson rest frame sampled by CLEO [56] applied. The uncertainty band is calculated from the D-meson $v_2$ uncertainties assuming that with removing the mass effect by $m_T - m_0$, the B-meson $v_2$ and D-meson $v_2$ are the same. The $v_2^{b-e}$ of this work deviates from the red dashed curve at $3 < p_T < 7$ GeV/c with a 4.50-$\sigma$ significance ($\chi^2/ndf = 31.73/5$), and this may indicate that the heavy quark elliptic flow is smaller than that of light and charm quarks which follow the NCQ scaling because the beauty quarks may be too heavy to thermalize and to move with the collective flow of light quarks. The TAMU model predictions [48, 49, 50] shown as pink dot-dashed curves ($v_2^{b-e}$) and violet dot-dot-dashed curves ($v_2^{b-e}$) are consistent with results of this work at $p_T \gtrsim 4$ GeV/c, while they, especially the $v_2^{b-e}$, deviate from data at low $p_T$. Another theoretical predictions by PHSD model [51] are also shown as the black long-dashed curve ($v_2^{\text{ince}}$) and green dot-dot-dashed curve ($v_2^{b-e}$), which agree with data better, but the prediction of $v_2^{b-e}$ still underestimates the data. In a previous work, a compilation of calculations of the dimensionless heavy quark diffusion coefficient, $2\pi T D_j$, that describe the $v_2$ and $R_{AA}$ of D-mesons, is constrained in the range of 1.5–7 at the critical temperature $T_c$ [52]. In this work, since we only separate the electron contributions from charm and beauty decays, the charm diffusion coefficient extracted from the electron $R_{AA}$ and $v_2$ from charm decays should be consistent with that extracted from open charm hadrons. The conclusion about the charm diffusion coefficient will not change. However, there is very little discussion on the beauty diffusion coefficient from theoretical calculations due to absence of the measurement on open beauty hadrons in heavy-ion collisions. Usually the heavy flavor spatial diffusion coefficients at zero-momentum reflect the long-wavelength structure of the QCD medium. Therefore, the theoretical treatment of the spatial diffusion coefficients for charm and bottom should be the same. However, there may be some difference practically between them because the large mass approximation may not work the same way for charm and bottom. Testing the universality of heavy quark spatial diffusion coefficients between charm and bottom is an important next step to constrain the theoretical uncertainties and provide a deep understanding on the QGP microscopic dynamics. Our results could provide a new reference for further theoretical calculations. Especially the electron $R_{AA}$ and $v_2$ from beauty decays for both RHIC and

### Table 4
Uncertainty components of $R_{\text{AA}}^{\text{ince}}$ and $R_{\text{AA}}^{\text{b-e}}$

| Centrality | $f_{\text{PbPb}}^{b-e}$ | $f_{\text{PbPb}}^{\text{ince}}$ | $f_{\text{PbPb}}^{b-e}$ | $f_{\text{PbPb}}^{\text{ince}}$ | $\delta (R_{\text{AA}}^{\text{ince}})$ | $\delta (R_{\text{AA}}^{\text{b-e}})$ |
|------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0–10%      | 30–50%        | 0–10%         | 30–50%        | 0–10%         | 30–50%         | 0–10%         |
| $\delta (R_{\text{AA}}^{\text{ince}})$ | 13.0%–17.5% | 13.1%–14.9% | 5.0%–6.7% | 5.0%–6.7% | 10.5%–17.4% | 11.1%–17.4% | 17.5%–24.0% | 18.3%–23.7% |
| $\delta (R_{\text{AA}}^{\text{b-e}})$ | 5.0%–13.4% | 6.4%–13.7% | 4.0%–7.6% | 4.0%–7.6% | 10.5%–17.4% | 11.1%–17.4% | 12.8%–20.3% | 14.9%–19.2% |
LHC energies may provide different results for theoretical calculations to extract the QGP transport parameters with different temperatures.

3. Summary

This paper presents an isolation of charm and beauty contributions from heavy flavor decay electrons in p+p and Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at LHC. The $p_T$ spectra, $R_{AA}$ at 0–10% and 30–50% centrality classes and $v_2$ at 30–50% centrality of electrons from charm and beauty decays at mid-rapidity in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are reported.

The electron $R_{AA}$ from charm ($R^{c}\to e$) and beauty ($R^{b}\to e$) decays are suppressed at $p_T > 2.0$ GeV/$c$ in Pb+Pb collisions, respectively, which indicates that charm and beauty quarks interact with the hot-dense medium and lose their energy. The $R^{c}\to e$ at $2.0 < p_T < 8.0$ GeV/$c$ and $R^{b}\to e$ at $4.0 < p_T < 8.0$ GeV/$c$ are more suppressed at 0–10% centrality than at 30–50% centrality, which suggests that heavy quarks lose more energy in the medium created in more central collisions. However, at low $p_T < 4.0$ GeV/$c$, $R^{b}\to e$ shows no significant centrality dependence. A less suppression of electron $R_{AA}$ from beauty decays compared with that from charm decays in the whole $p_T$ region from 2.0 to 8.0 GeV/$c$ is observed, which is consistent with the mass-dependent partonic energy loss mechanism. A non-zero electron $v_2$ from beauty decays ($v_{2}^{b\to e}$) is observed and consistent with the ALICE measurement in the overlapping $p_T$ region. At low $p_T$ from 1.0 to 3.0 GeV/$c$, a discrepancy between results in 200 GeV Au+Au collisions and in 5.02 TeV Pb+Pb collisions is observed with an 85% confidence level, which might be a hint that beauty quark reacts differently to the two different media created in the heavy-ion collisions with two very different collision energies. At 3.0 GeV/$c < p_T < 7.0$ GeV/$c$, $v_{2}^{b\to e}$ deviates from a NCQ scaling hypothesis, which favors that beauty quark is unlikely thermalized even in such high energy heavy-ion collisions at LHC. The $R_{AA}$ and $v_2$ results of electrons with charm and beauty contribution separation could provide a new reference for theoretical models to extract the beauty diffusion coefficient with further theoretical calculations.

Acknowledgments: This work was supported by National Natural Science Foundation of China with Grant No. 11890712 and 12061141008, National Key Research and Development Program of China with Grant No. 2018YFE0104700 and 2018YFE0205200, Strategic Priority Research Program of Chinese Academy of Sciences with Grant No. XDB34000000, and Anhui Provincial Natural Science Foundation with Grant No. 1808085J02.

Dongsheng Li and Fan Si contribute equally to this work as first co-authors.

References

[1] Gyulassy, M., 2004. The QGP discovered at RHIC, in: NATO Advanced Study Institute: Structure and Dynamics of Elementary Matter, pp. 159–182, arXiv:nucl-th/0403032.
[2] Bass, S.A., Gyulassy, M., Stoecker, H., Greiner, W., 1999. Signatures of quark gluon plasma formation in high-energy heavy ion collisions: A Critical review. J. Phys. G 25, R1-R57. doi:10.1088/0954-3899/25/3/013, arXiv:hep-ph/9810281.
[3] Karsch, F., 1995. The Phase transition to the quark gluon plasma: Recent results from lattice calculations. Nucl. Phys. A 590, 367C-382C. doi:10.1016/0375-9474(95)00238-9, arXiv:hep-lat/9503010.
[4] Moore, G.D., Teaney, D., 2005. How much do heavy quarks thermalize in a heavy ion collision? Phys. Rev. C 71, 064904. doi:10.1103/PhysRevC.71.064904, arXiv:hep-ph/0412346.
[5] Tang, Z.B., Zha, W.M., Zhang, Y.F., 2020. An experimental review of open heavy flavor and quarkonium production at RHIC. Nucl. Sci.
Charm and beauty isolation from heavy flavor decay electrons in p+p and Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at LHC

[42] Sjostrand, T., Mrenna, S., Skands, P.Z., 2006. PYTHIA 6.4 Physics and Manual. JHEP 05, 026. doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[43] Liu, H.d., Zhang, Y.f., Zhong, C., Xu, Z.b., 2006. Extract charm cross section from its semileptonic decay at RHIC. Phys. Lett. B 639, 441–446. doi:10.1016/j.physletb.2006.07.008, arXiv:nucl-ex/0601030.

[44] Acharya, S., et al. (ALICE Collaboration), 2021. First measurement of quarkonium polarization in nuclear collisions at the LHC. Phys. Lett. B 815, 136146. doi:10.1016/j.physletb.2021.136146, arXiv:2005.11128.

[45] Tanabashi, M., et al. (Particle Data Group), 2018. Review of Particle Physics. Phys. Rev. D 98, 030001. doi:10.1103/PhysRevD.98.030001.

[46] Cacciari, M., Greco, M., Nason, P., 1998. The $P(T)$ spectrum in heavy flavor hadroproduction. JHEP 05, 007. doi:10.1088/1126-6708/1998/05/007, arXiv:hep-ph/9803400.

[47] Park, J. (ALICE Collaboration), 2021. Nuclear modification factor of electrons from open beauty-hadron decays in PbPb collisions at $\sqrt{s_{NN}}=5.02$ TeV with ALICE. PoS HardProbes2020, 034. doi:10.22323/1.387.0034.

[48] Cao, S., Qin, G.Y., Bass, S.A., 2013. Heavy-quark dynamics and hadronization in ultrarelativistic heavy-ion collisions: Collisional versus radiative energy loss. Phys. Rev. C 88, 044907. doi:10.1103/PhysRevC.88.044907, arXiv:1308.0617.

[49] Cao, S., Qin, G.Y., Bass, S.A., 2015. Energy loss, hadronization and hadronic interactions of heavy flavors in relativistic heavy-ion collisions. Phys. Rev. C 92, 024907. doi:10.1103/PhysRevC.92.024907, arXiv:1505.01413.

[50] Li, S.Q., Xing, W.J., Liu, F.L., Cao, S., Qin, G.Y., 2020. Heavy flavor quenching and flow: the roles of initial condition, pre-equilibrium evolution, and in-medium interaction. Chin. Phys. C 44, 114101. doi:10.1088/1674-1137/abadee, arXiv:2005.0330.

[51] Song, T., Cassing, W., Moreau, P., Bratkovskaya, E., 2018. Open charm and dileptons from relativistic heavy-ion collisions. Phys. Rev. C 97, 064907. doi:10.1103/PhysRevC.97.064907, arXiv:1803.02608.

[52] Acharya, S., et al. (ALICE Collaboration), 2018. $D$-meson azimuthal anisotropy in midcentral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Rev. Lett. 120, 102301. doi:10.1103/PhysRevLett.120.102301, arXiv:1707.01005.

[53] Acharya, S., et al. (ALICE Collaboration), 2017. $J/\psi$ elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Phys. Rev. Lett. 119, 242301. doi:10.1103/PhysRevLett.119.242301, arXiv:1709.05268.

[54] Zhou, K., Xu, N., Xu, Z., Zhuang, P., 2014. Medium effects on charmonium production at ultrarelativistic energies available at the CERN Large Hadron Collider. Phys. Rev. C 89, 054911. doi:10.1103/PhysRevC.89.054911, arXiv:1401.5845.

[55] Moreira De Godoy, D. (ALICE Collaboration), 2017. Measurements of the nuclear modification factor and elliptic flow of leptons from heavy-flavour hadron decays in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV with ALICE. Nucl. Phys. A 967, 636–639. doi:10.1016/j.nuclphysa.2017.05.056, arXiv:1705.02800.

[56] Jain, V. (CLEO Collaboration), 1996. Recent results from CLEO on charm and bottom hadrons. Nucl. Phys. B Proc. Suppl. 50, 96–102. doi:10.1016/0920-5632(96)00372-6, arXiv:hep-ex/9601002.