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Azimuthal anisotropy of electrons from heavy flavor decays in $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ Au-Au collisions at PHENIX

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Abstract. The PHENIX experiment has measured the azimuthal anisotropy parameter v_2, the second harmonic of the azimuthal distribution, for electrons at mid-rapidity ($|\eta| < 0.35$) as a function of transverse momentum ($0.5 < p_\mathrm{T}\,(\mathrm{GeV}/c) < 5.0$) in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. From the result we have calculated the non-photonic electron v_2, which is expected to reflect charm quark azimuthal anisotropy, by subtracting the v_2 of electrons from other sources such as photon conversions and Dalitz decays.

1 Introduction

Charm quarks are believed to be produced in initial collisions via gluon fusion and to propagate through the hot and dense medium created in the collisions. Therefore charm can be used as a probe to study the medium created in heavy ion collisions. At RHIC energies, charm quark energy loss [1] and charm flow [2] have been proposed as powerful probes to study the properties of the medium created in Au+Au collisions. Because of their large mass, charm quarks are predicted to lose less energy than light quarks. A recent study of charm via electron measurements suggests that the charm quark energy loss is larger than expected in the medium created in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ [3]. The azimuthal anisotropy of particle emissions is a powerful tool to study flow in ultra-relativistic nuclear collisions, and it provides another way to study the effects of the medium on charm quarks. The azimuthal anisotropy is defined by

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = N_0 \left\{ 1 + \sum_n 2\,\mathrm{v_n} \cos(n(\phi - \Psi_{\mathrm{R.P.}})) \right\}, \qquad (1)$$

where N_0 is a normalization constant, ϕ is the azimuthal angle of the particle, and $\Psi_{\mathrm{R.P.}}$ is the direction of the nuclear impact parameter ("reaction plane") in a given collision. The harmonic coefficients, v_n, indicate the strength of the n^{th} anisotropy. The transverse momentum (p_T) dependence of the elliptic flow, which is the second harmonic coefficient of the Fourier expansion of the azimuthal distribution (v_2), has been measured for identified particles at RHIC. One of the biggest discoveries at RHIC is that the v_2 for hadrons made from u, d and s quarks scales with the number of constituent quarks. This result suggests that the v_2 for hadrons made from u, d and s quarks develops in the partonic phase. This scaling behavior is consistent with predictions of the quark coalescence model, which assumes a finite v_2 of quarks [5]. If charm quarks flow like light quarks, it would indicate an unexpectedly strong interaction of charm with the medium.

Charm production can be studied by measuring electrons from their semi-leptonic decays in the PHENIX experiment at RHIC [3, 6–8]. In this paper, we present the measurement of the single electron v_2, which is expected to reflect primarily the charm quark azimuthal anisotropy below $5\,\mathrm{GeV}/c$ with respect to the reaction plane in Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. The non-photonic electron v_2 was measured by subtracting from the inclusive electron v_2, the v_2 of electrons from other sources such as photon conversions and Dalitz decays from light neutral mesons.

2 Method

The inclusive electron sample has two components: (1) "non-photonic" – primarily semi-leptonic decays of mesons containing heavy (charm and bottom) quarks, and (2) "photonic" – Dalitz decays of light neutral mesons (π_0, η, η', ω and ϕ) and photon conversions in the detector material [7]. The azimuthal distribution of electrons ($\mathrm{d}N_\mathrm{e}/\mathrm{d}\phi$) is the sum of the azimuthal distributions of photonic electrons ($\mathrm{d}N_\mathrm{e}^\gamma/\mathrm{d}\phi$) and non-photonic electrons ($\mathrm{d}N_\mathrm{e}^{\mathrm{non}-\gamma}/\mathrm{d}\phi$):

$$\frac{\mathrm{d}N_\mathrm{e}}{\mathrm{d}\phi} = \frac{\mathrm{d}N_\mathrm{e}^\gamma}{\mathrm{d}\phi} + \frac{\mathrm{d}N_\mathrm{e}^{\mathrm{non}-\gamma}}{\mathrm{d}\phi}\,. \qquad (2)$$

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From (2), the inclusive electron v_2 is given by:

$$N_{\mathrm{e}}v_{2_{\mathrm{e}}} = N_{\mathrm{e}}^{\gamma}v_{2_{\mathrm{e}}}^{\gamma} + N_{\mathrm{e}}^{\mathrm{non}-\gamma}v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma}\,. \tag{3}$$

In this analysis the non-photonic electron v_2 is determined by two methods. In the first method, the non-photonic electron v_2 is calculated by using the inclusive electron v_2 measured with and without a thin converter around the collision region (the converter method). The yield of electrons with and without the converter can be written as,

$$\begin{aligned} N_{\mathrm{e}}^{\text{conv-in}} &= R_{\gamma}N_{\mathrm{e}}^{\gamma} + N_{\mathrm{e}}^{\mathrm{non}-\gamma} \\ N_{\mathrm{e}}^{\text{conv-out}} &= N_{\mathrm{e}}^{\gamma} + N_{\mathrm{e}}^{\mathrm{non}-\gamma}\,. \end{aligned} \tag{4}$$

where R_{γ} is the ratio of the number of photonic electrons with and without converter. From (3) and (4) the relation between the number of electrons and the values of v_2 are given as;

$$\begin{aligned} N_{\mathrm{e}}^{\text{conv-in}}v_{2}^{\text{conv-in}} &= R_{\gamma}N_{\mathrm{e}}^{\gamma}v_{2_{\mathrm{e}}}^{\gamma} + N_{\mathrm{e}}^{\mathrm{non}-\gamma}v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma}\,, \\ N_{\mathrm{e}}^{\text{conv-out}}v_{2}^{\text{conv-out}} &= N_{\mathrm{e}}^{\gamma}v_{2}^{\gamma} + N_{\mathrm{e}}^{\mathrm{non}-\gamma}v_{2}^{\mathrm{non}-\gamma}\,. \end{aligned} \tag{5}$$

where $v_{2_{\mathrm{e}}}^{\text{conv-in}}$ is the inclusive electron v_2 measured with converter and $v_{2_{\mathrm{e}}}^{\text{conv-out}}$ is the inclusive electron v_2 measured without the converter. From (5) the value of $v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma}$ is obtained as:

$$v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma} = \frac{R_{\gamma}(1+R_{\mathrm{NP}})v_{2_{\mathrm{e}}}^{\text{conv-out}} - (R_{\gamma}+R_{\mathrm{NP}})v_{2_{\mathrm{e}}}^{\text{conv-in}}}{R_{\mathrm{NP}}(R_{\gamma}-1)}\,. \tag{6}$$

where R_{NP} is the ratio of the number of non-photonic electrons to photonic electrons ($N_{\mathrm{e}}^{\mathrm{non}-\gamma}/N_{\mathrm{e}}^{\gamma}$). The ratio is experimentally determined from analysis of converter-in runs. The measured ratio is shown in Fig. 1. R_{NP} is larger than 1.0 above 1.5 GeV/c, meaning that more than 50% of electrons come from non-photonic sources above 1.5 GeV/c. The value of $v_{2_{\mathrm{e}}}^{\gamma}$ is also obtained as:

$$v_{2_{\mathrm{e}}}^{\gamma} = \frac{(1+R_{\mathrm{NP}})v_{2_{\mathrm{e}}}^{\text{conv-out}} - (R_{\gamma}+R_{\mathrm{NP}})v_{2_{\mathrm{e}}}^{\text{conv-in}}}{(1-R_{\gamma})}\,. \tag{7}$$

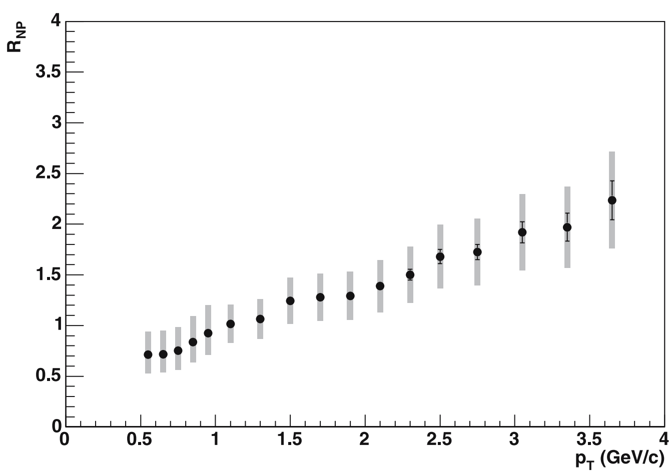

Fig. 1. The transverse momentum dependence of the ratio of the number of non-photonic electrons to photonic electrons ($N_{\mathrm{e}}^{\mathrm{non}-\gamma}/N_{\mathrm{e}}^{\gamma}$)

In the second method, the non-photonic electron v_2 is calculated by subtracting the photonic electron v_2 estimated by Monte Carlo simulation (the cocktail method). From (3)

$$\begin{aligned} v_{2_{\mathrm{e}}} &= \frac{N_{\mathrm{e}}^{\gamma}v_{2_{\mathrm{e}}}^{\gamma} + N_{\mathrm{e}}^{\mathrm{non}-\gamma}v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma}}{N_{\mathrm{e}}^{\gamma} + N_{\mathrm{e}}^{\mathrm{non}-\gamma}} \\ &= \frac{v_{2_{\mathrm{e}}}^{\gamma} + R_{\mathrm{NP}}v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma}}{1+R_{\mathrm{NP}}}\,, \end{aligned}$$

therefore $v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma}$ can be expressed as

$$v_{2_{\mathrm{e}}}^{\mathrm{non}-\gamma} = \frac{(1+R_{\mathrm{NP}})v_{2_{\mathrm{e}}} - v_{2_{\mathrm{e}}}^{\gamma}}{R_{\mathrm{NP}}}\,. \tag{8}$$

We apply the converter method below 1.0 GeV/c and the cocktail method above 1.0 GeV/c due to the limited statistics in the converter runs.

3 Results and discussion

This analysis is based on PHENIX data from RHIC Run 4, in 2004 to 2005. In PHENIX, electrons are identified by a Ring Image Cherenkov detector (RICH) and an Electromagnetic Calorimeter (EMC). The electron candidates are required to have at least three associated hits in the RICH that pass a ring shape cut. In addition, energy is measured in the EMCal, and momentum matching (E/p) is required to reduce background from hadrons and photon conversions far from the vertex. Electrons deposit all of their energy in the EMCal; therefore the E/p is approximately 1.0. In this analysis we require $-2\sigma < (E-p)/p < 3\sigma$ to reduce background. The value of v_2 is obtained by the reaction plane method which measures the particle azimuthal angle with respect to the reaction plane. The reaction plane is determined by Beam–Beam Counters (BBC) installed upstream and downstream of PHENIX. Since each BBC is roughly three units of pseudorapidity away from the central arms, it is expected that non-flow effects are small [4]. Figure 2 shows the inclusive electron v_2 with and without the photon converter. If the v_2 of the photonic electrons and non-photonic electrons would be identical, the inclusive electron v_2 measured with and without converter would be the same. But the v_2 measured with and without converter are different, indicating that the v_2 of the photonic electrons and non-photonic electrons is different.

The transverse momentum dependence of the photonic electron v_2 is shown in Fig. 3 together with the inclusive electron v_2 measured without the converter. The photonic electron v_2 obtained from the converter method is shown as open circles and the photonic electron v_2 obtained by

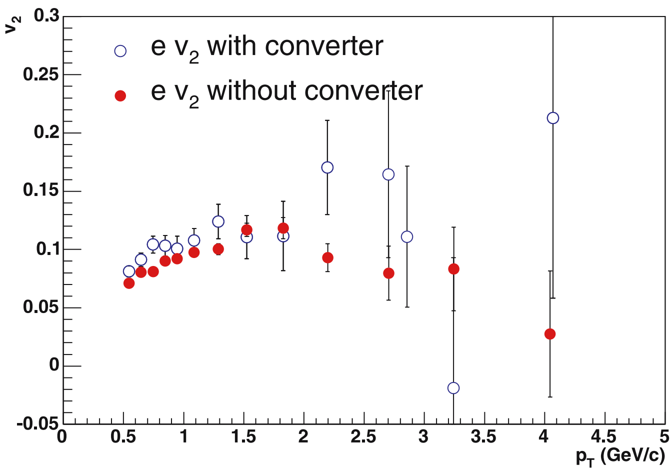

Fig. 2. Inclusive electron v_2 measured with and without the converter as a function of p_T

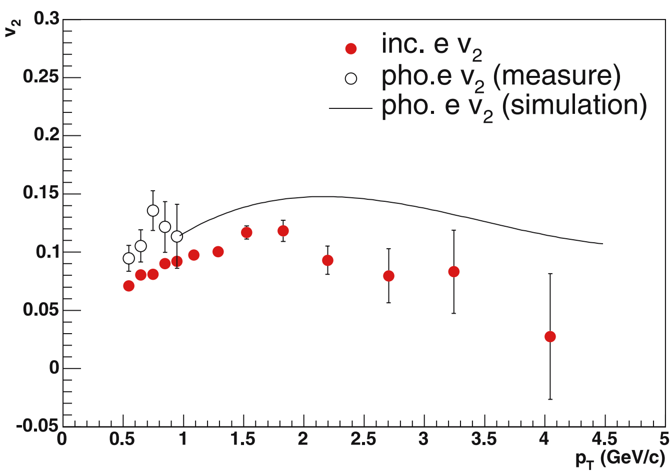

Fig. 3. The transverse momentum dependence of the photonic electron v_2 together with the inclusive electron v_2. The photonic electron v_2 obtained from the converter method is shown as open circles and the v_2 obtained from the Monte Carlo simulation is shown as *solid line*

Monte Carlo simulation using the measured parent p_T distribution and v_2 is shown as the solid line. The inclusive electron v_2 is smaller than the photonic electron v_2, which means that the non-photonic electron v_2 is smaller than both of them. The transverse momentum dependence of the non-photonic electron v_2 is shown in Fig. 4. Below 1 GeV/c the non-photonic electron v_2 is determined by the converter method and above 1 GeV/c it is determined by the cocktail method. The statistical errors are shown as vertical lines and the 1 σ systematic uncertainties are shown as brackets. The non-photonic electron v_2 increases with p_T until it saturates at about 1.5 GeV/c.

The non-photonic electrons arise mainly from D meson decay [6]. The v_2 of electrons from D meson decay has been studied by Monte Carlo simulations [9] and the electron v_2 reflects D meson v_2. Therefore the large non-photonic electron v_2 indicates that the D meson has large v_2. We have estimated the transverse momentum dependence of

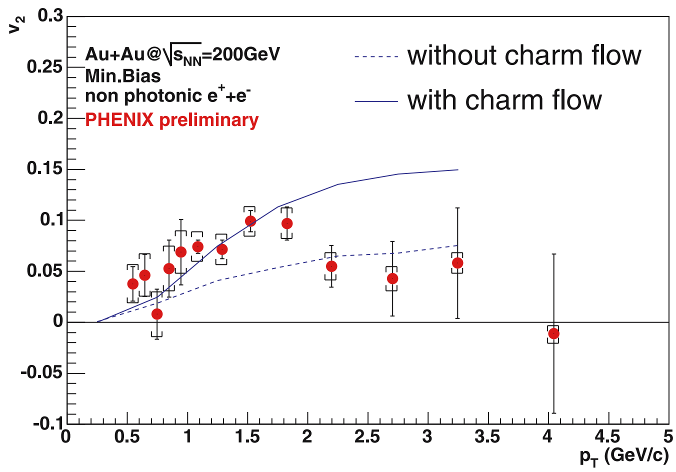

Fig. 4. The transverse momentum dependence of the non-photonic electron v_2. The lines on the figure represent the electron v_2 from D meson decay based on the quark coalescence model. The *solid line* is the electron v_2 from D meson decay with charm quark flow ($v_{2,\mathrm{charm}} \neq 0$) and the *dashed line* is from D meson decay without charm flow ($v_{2,\mathrm{charm}} = 0$)

the D meson v_2 by using the non-photonic electron v_2 below 2.0 GeV/c. In this calculation we assumed that all non-photonic electrons are from D meson decay and the transverse momentum dependence of D meson v_2 ($v_2^D(p_\mathrm{T})$) is given by:

$$v_2^D(p_\mathrm{T}) = a \times f(p_\mathrm{T}) \tag{9}$$

where $f(p_\mathrm{T})$ is the D meson v_2 shape and a is a scale factor for $f(p_\mathrm{T})$. Here we assumed that the shape of $v_2(p_\mathrm{T})$ of the D meson is the same as that of the pion, kaon or proton, which where obtained by fits to their measured values. The scale factor (a) was determined in each of the three cases by calculating chi-squared for a comparison of the electron v_2 shape obtained by Monte Carlo simulation of the D meson decay and the measured non-photonic electron v_2 using:

$$\chi^2 = \Sigma\{\left(v_2^{\mathrm{non}-\gamma} - v_2^{D\to\mathrm{e}}\right)/\sigma_{v_2}\}^2 \tag{10}$$

where $v_2^{\mathrm{non}-\gamma}$ is the measured non-photonic electron v_2, $v_2^{D\to\mathrm{e}}$ is the electron v_2 obtained by Monte Carlo simulation of the D meson decay and σ is the statistical error of the measured non-photonic electron v_2. Figure 5 shows the χ^2/ndf as a function of the scale factor for each of the three assumed v_2 shapes. Figure 6 shows the D meson v_2 ($v_2^D(p_\mathrm{T}) = a_{\chi^2_{\mathrm{mim.}}} \times f(p_\mathrm{T})$) estimated from the three calculations. These calculations lead D meson v_2 values extracted from the measured non-photonic electron v_2 are smaller than those for the pion v_2 and larger than those for the deuteron.

The v_2 of D meson decay electrons has been predicted [10] using a quark coalescence model. In the model, D mesons are formed by charm quark coalescence with thermal light quarks at hadronization. The solid line in Fig. 4 is the decay electron v_2 from D mesons with charm

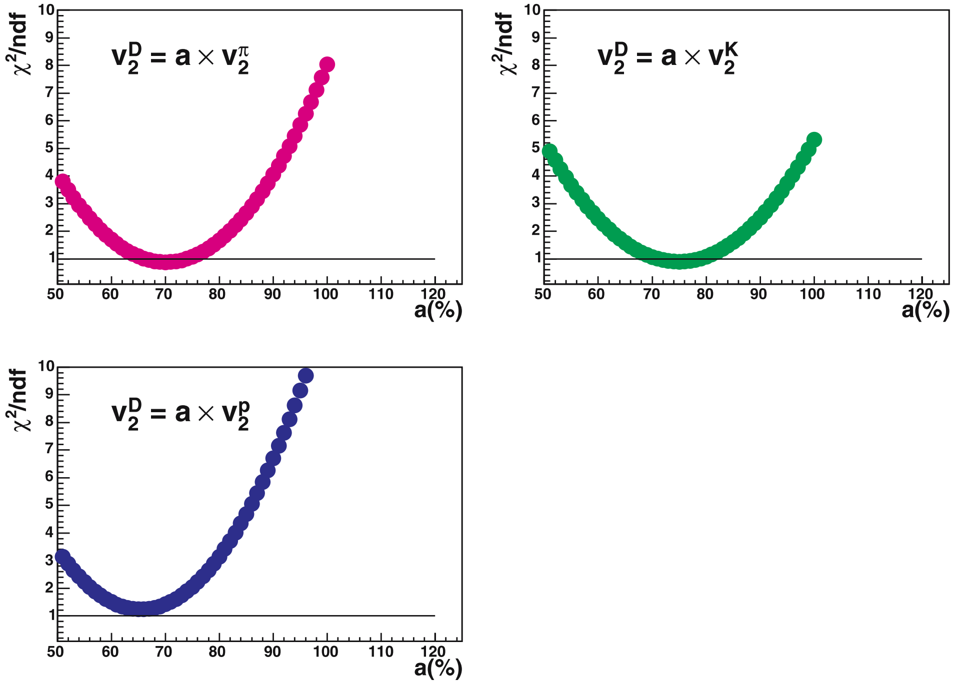

Fig. 5. Results of the χ^2 test between measured non-photonic electron v_2 and electron v_2 calculated by simulation assuming D meson v_2 shape as a function of scaled parameter a (%)

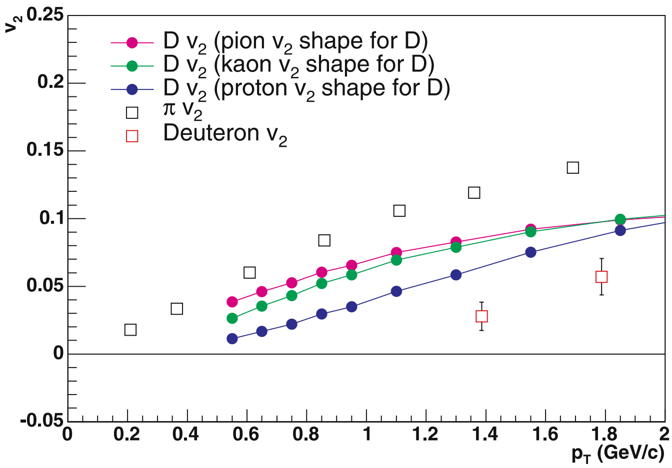

Fig. 6. Expected D meson v_2 extracted from the measured non-photonic electron v_2 using various assumptions for the D v_2 p_T dependence, namely that it is the same shape as the pion, kaon and proton v_2. The pion and deuteron v_2 in the figure are PHENIX preliminary results from Run 4

quark flow ($v_{2,\mathrm{charm}} \neq 0$) and the dashed line is from D mesons without charm flow ($v_{2,\mathrm{charm}} = 0$). Even if the charm quark v_2 is zero, the electron v_2 is non zero because the u quark that coalesces with the charm quark has non-zero v_2. Below 2.0 GeV/c the non-photonic electron v_2 is in good agreement with the electron v_2 obtained by assuming charm quark flow. In the model, the charm quark v_2 is assumed to be smaller than the u quark v_2 at low p_{T}. Therefore the consistency indicates not only that the charm quark v_2 is non-zero, but also that it is smaller than that for the u quark.

The contributions to non-photonic electrons from B meson decays is model dependent. The B contribution might be larger than the D contribution at high p_{T}. Due to the larger mass of the B, the v_2 might be smaller than that for the D, in which case the electron v_2 from the B will also be smaller than that from the D. The non-photonic electron v_2 including B decay contributions has been calculated. The model predicts that at high p_{T} the non-photonic electron v_2 with B decay contributions is smaller than the non-photonic v_2 without B decay contributions [11]. The present non-photonic electron v_2 has large statistical uncertainties at high p_{T}. For the next RHIC run (Run 7) a new reaction plane detector has been installed in PHENIX. It provides about two times better reaction plane resolution than the BBC, and will allow improved precision for studying the high p_{T} non-photonic electron v_2.

4 Summary

In this paper we present measurements of the transverse momentum dependence of the non-photonic electron v_2, which is expected to reflect the charm quark azimuthal anisotropy, measured with the PHENIX experiment in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We observe a relatively large v_2. We compare our results with the quark coalescence model predictions with or without charm quark flow. Below 2.0 GeV/c the non-photonic electron v_2 is well described with a model of the electron v_2 obtained by assuming that charm quarks flow before coalescing into D mesons. We have extracted the D meson v_2 from the electron data by arbitrarily assuming several v_2 shapes. When it is assumed that the D meson v_2 shape is the same as that for the pion, kaon or proton, the D meson v_2 extracted from the measured non-photonic electron v_2 is smaller than the pion v_2 and larger than the deuteron v_2.

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