

## Energy Loss and Flow of Heavy Quarks in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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The PHENIX experiment at the BNL Relativistic Heavy Ion Collider (RHIC) has measured electrons with  $0.3 < p_T < 9$  GeV/ $c$  at midrapidity ( $|\eta| < 0.35$ ) from heavy-flavor (charm and bottom) decays in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The nuclear modification factor  $R_{AA}$  relative to  $p + p$  collisions shows a strong suppression in central Au + Au collisions, indicating substantial energy loss of heavy quarks in the medium produced at RHIC energies. A large azimuthal anisotropy  $v_2$  with respect to the reaction plane is observed for  $0.5 < p_T < 5$  GeV/ $c$  indicating substantial heavy-flavor elliptic flow. Both  $R_{AA}$  and  $v_2$  show a  $p_T$  dependence different from those of neutral pions. A comparison to transport models which simultaneously describe  $R_{AA}(p_T)$  and  $v_2(p_T)$  suggests that the viscosity to entropy density ratio is close to the conjectured quantum lower bound, i.e., near a perfect fluid.

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Experimental results from the Relativistic Heavy Ion Collider (RHIC) have established that dense partonic matter is formed in Au + Au collisions at RHIC [1–4]. Strong suppression observed for  $\pi^0$  and other light hadrons at high transverse momentum ( $p_T$ ) [5–8] indicates partonic energy loss in the produced medium. The azimuthal anisotropy  $v_2(p_T)$  [9,10] provides evidence that collective motion develops in a very early stage of the collision ( $\tau \lesssim 5$  fm/ $c$ ), in accordance with hydrodynamical calculations [11,12]. The comparison of  $v_2$  with several such models suggests [13–15] that the matter formed at RHIC is a near-perfect fluid with viscosity to entropy density ratio  $\eta/s$  close to the conjectured quantum lower bound [16]. Energy loss and flow are related to the transport properties of the medium at temperature  $T$ , in particular, the diffusion coefficient  $D \propto \eta/(sT)$ .

Further insight into properties of the medium can be gained from the production and propagation of particles carrying heavy quarks (charm or bottom). A fixed-order-plus-next-to-leading-log (FONLL) perturbative QCD (pQCD) calculation [17] describes the cross sections of heavy-flavor decay electrons in  $p + p$  collisions at  $\sqrt{s} = 200$  GeV within theoretical uncertainties [18]. In Au + Au collisions the total yield of such electrons was found to scale with the number of nucleon-nucleon collisions as expected for pointlike processes [19]. Energy loss via gluon radiation is expected to be reduced for heavy quarks due to suppression of forward radiation, thus increasing their expected thermalization time [20–22]. Consequently, a decrease of high  $p_T$  suppression and of  $v_2$  is expected from light to charm to bottom quarks, with the absolute values and their  $p_T$  dependence sensitive to the properties of the medium. In contrast to these expectations, a strong suppression of heavy-flavor decay electrons was discovered for  $2 < p_T < 5$  GeV/ $c$  [23,24], together with nonzero electron  $v_2$  for  $p_T < 2$  GeV/ $c$  [25].

This Letter presents  $p_T$  spectra and the elliptic flow amplitude  $v_2^{\text{HF}}$  of electrons,  $(e^+ + e^-)/2$ , from heavy-flavor decays at midrapidity in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. An increase in statistics by more than a factor of 10 and reduced systematic uncertainties compared to earlier data [19,23,25] greatly extend the  $p_T$  range both for the determination of the centrality dependence of  $R_{AA}$  and for the measurement of  $v_2^{\text{HF}}$ .

The data were collected by the PHENIX detector [26] in the 2004 RHIC run. The minimum bias trigger and the collision centrality were obtained from the beam-beam counters (BBC) and zero degree calorimeters [1]. After selecting good runs, data samples of  $8.1$  and  $7.0 \times 10^8$  minimum bias events in the vertex range  $|z_{\text{vtx}}| < 20$  cm are used for the spectra and  $v_2$  analyses, respectively.

Charged particle tracks are reconstructed with the two PHENIX central arm spectrometers, each covering  $\Delta\phi = \pi/2$  in azimuth and  $|\eta| < 0.35$  in pseudorapidity [26]. Tracks are confirmed by matching showers in the electromagnetic calorimeter (EMC) within  $2\sigma$  in position. Electron candidates have at least three associated hits in the ring imaging Čerenkov detectors (RICH) and fulfill a shower shape cut in the EMC, where they deposit an energy  $E$ , consistent with the momentum  $(E/p - 1 > -2\sigma)$ . Below the Čerenkov threshold for pions ( $p_T < 5$  GeV/ $c$ ) electron misidentification is only due to random coincidences between hadron tracks and hits in the RICH. This small background ( $< 20\%$  at low  $p_T$  in central collisions, less toward high  $p_T$  and peripheral events) is subtracted statistically using an event mixing technique. Requiring at least five hits in the RICH and tightening the shower shape cut extends the electron measurement to 9 GeV/ $c$  in  $p_T$ , with negligible hadron background for  $p_T < 8$  GeV/ $c$  and a hadron contamination of 20% for  $8 < p_T < 9$  GeV/ $c$ . The raw spectra are corrected for geometrical acceptance and reconstruction efficiency de-



terminated by a GEANT simulation. The centrality dependent efficiency loss  $<2\%$  ( $\approx 23\%$ ) for peripheral (central) events is evaluated by reconstructing simulated electrons embedded into real events.

The inclusive electron spectra consist of (i) “nonphotonic” electrons from heavy-flavor decays, (ii) “photonic” background from Dalitz decays and photon conversions (mainly in the beam pipe), and (iii) nonphotonic background from  $K \rightarrow e\pi\nu$  ( $K_{e3}$ ) and dielectron decays of vector mesons. Contribution (iii) is small ( $<10\%$  for  $p_T < 0.5$  GeV/ $c$ ,  $<2\%$  for  $p_T > 2$  GeV/ $c$ ) compared to (ii). The heavy-flavor signal and the ratio of nonphotonic to photonic electrons,  $R_{NP}$ , are determined via two independent and complementary methods described in detail in [18], where the identical detector configuration was used. At low  $p_T$  ( $p_T < 1.6$  GeV/ $c$ ), where the heavy-flavor signal to background ratio is small ( $S/B < 1$ ), the “converter subtraction” method is used, which employs a photon converter of 1.67% radiation length ( $X_0$ ) installed around the beam pipe for part of the run. The converter multiplies the photonic background by a known, nearly  $p_T$  independent factor  $R_\gamma \sim 2.3$ . The photonic background can then be determined by comparing the inclusive electron yield with and without the converter. For higher  $p_T$ , where  $S/B$  is large, the “cocktail subtraction” method [23] is used. Here the background is calculated with a Monte Carlo hadron decay generator and subtracted from the data. At low  $p_T$  the dominant background source is the  $\pi^0$  Dalitz decay, which is calculated for each centrality using measured pion spectra [6,27] as input. In good agreement with measured data [8], the spectral shapes of other light hadrons ( $\eta$ ,  $\rho$ ,  $\omega$ ,  $\phi$ ,  $\eta'$ ) are derived from the pion spectrum assuming a universal shape in  $m_T = \sqrt{p_T^2 + m_h^2}$  with a fixed constant ratio at high  $p_T$ . Photon conversions in the beam pipe, air, and helium bags (total  $0.4\%X_0$ ) are also included, along with background from  $K_{e3}$  decays and both external and internal conversions of direct photons which are important for  $p_T > 4$  GeV/ $c$ . The agreement within the systematic uncertainties in the overlap region  $0.3 < p_T < 4$  GeV/ $c$  of these two methods demonstrates that the absolute value of photonic backgrounds in the PHENIX aperture is well understood.

The  $v_2$  of inclusive electrons,  $v_2^{\text{inc}}$ , is measured as  $v_2^{\text{inc}} = \langle \cos(2(\phi - \Phi_R)) \rangle / \sigma_R$  [28], where  $\Phi_R$  is the azimuthal orientation of the reaction plane measured with the resolution  $\sigma_R$  using the BBC [9]. Since  $\sigma_R$  is centrality dependent,  $v_2$  is determined for narrow centrality bins (10%) and then averaged to calculate  $v_2$  for minimum bias events. The  $v_2$  of random hadronic background is subtracted statistically as described in [25].

The  $v_2^{\text{non-}\gamma}$  of nonphotonic electrons is obtained by subtracting the photonic electron  $v_2^\gamma$  as  $v_2^{\text{non-}\gamma} = [(1 + R_{NP})v_2^{\text{inc}} - v_2^\gamma] / R_{NP}$ . Here  $v_2^\gamma$  is calculated via a Monte Carlo generator that includes  $\pi^0$ ,  $\eta$ , and direct photons. The measured  $v_2(p_T)$  of  $\pi^\pm$ ,  $\pi^0$ , and  $K^\pm$  [9,29]

is used as input, assuming  $v_2^{\pi^\pm} = v_2^{\pi^0}$ ,  $v_2^\eta = v_2^{K^\pm}$ , and  $v_2^{\text{direct } \gamma} = 0$ . A direct measurement of  $v_2^\gamma$  using the converter subtraction method confirms the calculation within statistical uncertainties. The resulting  $v_2^{\text{non-}\gamma}$  has a small contribution from  $K_{e3}$  background which is simulated and subtracted to obtain  $v_2^{\text{HF}}$  of heavy-flavor decay electrons.

Three independent categories of systematic uncertainties are considered. (a) The inclusive electron spectra include uncertainties in the geometrical acceptance (5%), the reconstruction efficiency (3%), and the embedding correction ( $\leq 4\%$ ). (b) Uncertainties in the converter subtraction are mainly given by the uncertainty in  $R_\gamma$  (2.7%) and in the relative acceptance of runs with and without the converter being installed (1%). (c) Uncertainties in the cocktail subtraction rise from 8% at  $p_T = 0.3$  GeV/ $c$  to 13% at 9 GeV/ $c$ , dominated by systematic errors in the pion input and, at high  $p_T$ , the direct photon spectrum. The  $v_2$  measurement includes a systematic uncertainty of 5% due to the reaction plane uncertainty.

Figure 1 shows the invariant  $p_T$  spectra of electrons from heavy-flavor decay for minimum bias events and in five centrality classes. The curves overlaid are the fit to the corresponding data from  $p + p$  collisions [18] with the spectral shape taken from a FONLL calculation [17] and scaled by the nuclear overlap integral  $\langle T_{AA} \rangle$  for each centrality class [6]. The inset of Fig. 1 shows the ratio of electrons from heavy-flavor decays to background. It increases rapidly with  $p_T$ , exceeding unity for  $p_T > 1.8$  GeV/ $c$ , reflecting the small amount of material in the detector acceptance which makes the accurate measurement of heavy-flavor electron spectra and  $v_2^{\text{HF}}$  possible.

For all centralities, the Au + Au spectra agree well with the  $p + p$  reference at low  $p_T$ , but a suppression with respect to  $p + p$  develops toward high  $p_T$ . This is quantified by the nuclear modification factor  $R_{AA} = dN_{\text{Au+Au}} / (\langle T_{AA} \rangle d\sigma_{p+p})$ , where  $dN_{\text{Au+Au}}$  is the differential yield in Au + Au and  $d\sigma_{p+p}$  is the differential cross section in  $p + p$  in a given  $p_T$  bin. For  $p_T < 1.6$  GeV/ $c$ ,  $d\sigma_{p+p}$  is taken bin-by-bin from [18], whereas a fit to the same data (curves in Fig. 1) is used at higher  $p_T$ , taking systematic uncertainties in  $d\sigma_{p+p}$  and  $T_{AA}$  into account.

Figure 2 shows  $R_{AA}$  for electrons from heavy-flavor decays for two different  $p_T$  ranges as a function of the number of participant nucleons  $N_{\text{part}}$ . For the integration interval  $p_T > 0.3$  GeV/ $c$  containing more than half of the heavy-flavor decay electrons [18],  $R_{AA}$  is consistent with unity for all  $N_{\text{part}}$  in accordance with the binary scaling of the total heavy-flavor yield [19]. For  $p_T > 3$  GeV/ $c$ , the heavy-flavor electron  $R_{AA}$  decreases systematically with centrality, while larger than  $R_{AA}$  of  $\pi^0$  with  $p_T > 4$  GeV/ $c$  [6]. Since above 3 GeV/ $c$  electrons from charm decays originate mainly from  $D$  mesons with  $p_T$  above 4 GeV/ $c$  this comparison indicates a smaller suppression of heavy-flavor mesons than observed for light mesons in this intermediate  $p_T$  range.

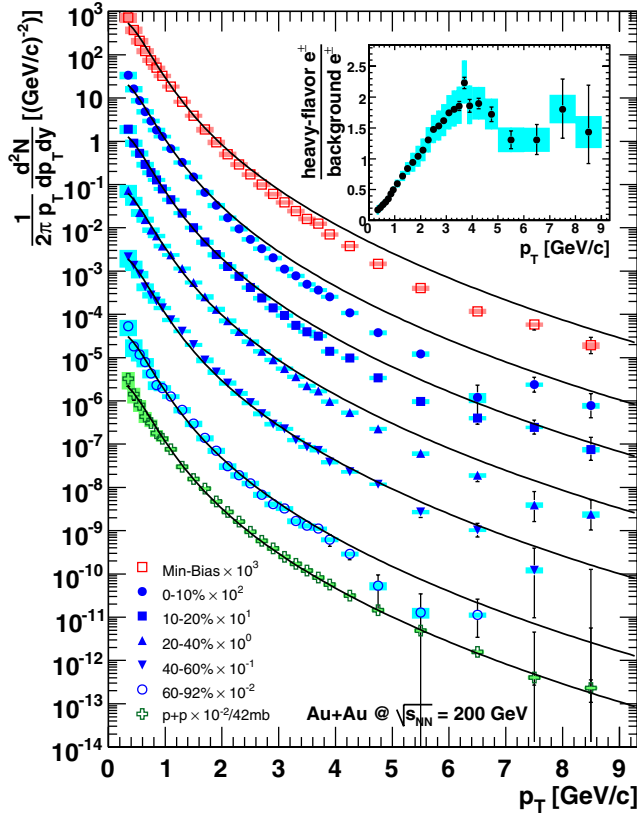


FIG. 1 (color online). Invariant yields of electrons from heavy-flavor decays for different Au + Au centrality classes and for  $p + p$  collisions, scaled by powers of 10 for clarity. The solid lines are the result of a FONLL calculation normalized to the  $p + p$  data [18] and scaled with  $\langle T_{AA} \rangle$  for each Au + Au centrality class. The inset shows the ratio of heavy-flavor to background electrons for minimum bias Au + Au collisions. Error bars (boxes) depict statistical (systematic) uncertainties.

Figure 3 shows the measured  $R_{AA}$  and  $v_2^{\text{HF}}$  of heavy-flavor electrons in 0%–10% central and minimum bias collisions, and our corresponding  $\pi^0$  data [6,29]. The data indicate strong coupling of heavy quarks to the medium. While at low  $p_T$  the suppression is smaller than that of  $\pi^0$ ,  $R_{AA}$  of heavy-flavor decay electrons approaches the  $\pi^0$  value for  $p_T > 4$  GeV/c although a significant contribution from bottom decays is expected at high  $p_T$ . The large  $v_2^{\text{HF}}$  indicates that the charm relaxation time is comparable to the short time scale of flow development in the produced medium. It should be noted that much reduced uncertainties and the extended  $p_T$  range of the present data permit the comparisons of  $R_{AA}$  and  $v_2$  of the heavy and light flavors.

More quantitative statements require theoretical guidance. Figure 3 compares the  $R_{AA}$  and  $v_2$  of heavy-flavor electrons with models calculating both quantities simultaneously. A pQCD calculation with radiative energy loss (curves I) [30] describes the measured  $R_{AA}$  reasonably well using a large transport coefficient  $\hat{q} = 14$  GeV<sup>2</sup>/fm, which also provides a consistent description of light hadron

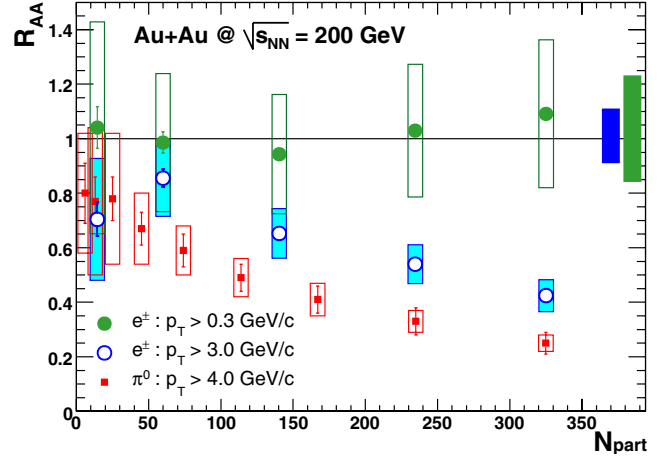


FIG. 2 (color online).  $R_{AA}$  of heavy-flavor electrons with  $p_T$  above 0.3 and 3 GeV/c and of  $\pi^0$  with  $p_T > 4$  GeV/c as function of centrality given by  $N_{\text{part}}$ . Error bars (boxes) depict statistical (point-by-point systematic) uncertainties. The right (left) box at  $R_{AA} = 1$  shows the relative uncertainty from the  $p + p$  reference common to all points for  $p_T > 0.3(3)$  GeV/c.

suppression. This value of  $\hat{q}$  would imply a strongly coupled medium. In this model the azimuthal anisotropy is only due to the path length dependence of energy loss, and the data clearly favor larger  $v_2^{\text{HF}}$  than predicted from this effect alone.

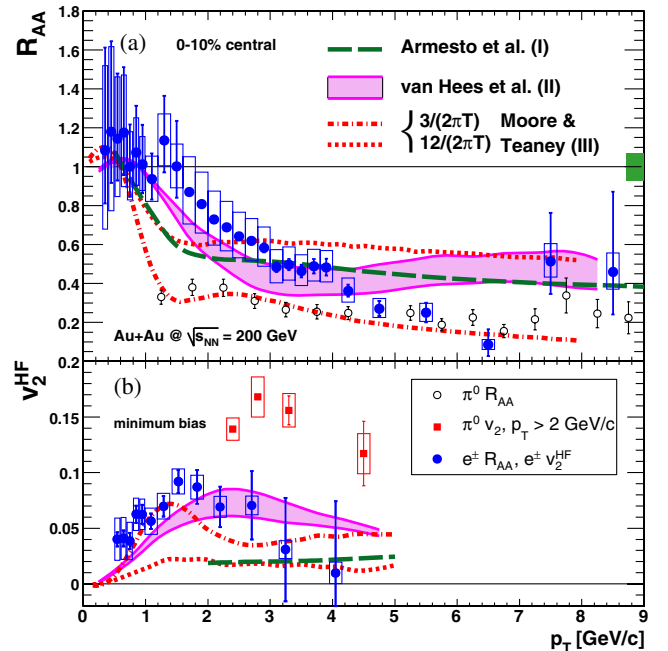


FIG. 3 (color online). (a)  $R_{AA}$  of heavy-flavor electrons in 0%–10% central collisions compared with  $\pi^0$  data [6] and model calculations (curves I [30], II [31], and III [32]). The box at  $R_{AA} = 1$  shows the uncertainty in  $T_{AA}$ . (b)  $v_2^{\text{HF}}$  of heavy-flavor electrons in minimum bias collisions compared with  $\pi^0$  data [29] and the same models. Errors are shown as in Fig. 2.

Figure 3 also shows that the large  $v_2^{\text{HF}}$  is better reproduced in Langevin-based heavy quark transport calculations [31,32]. A calculation which includes elastic scattering mediated by resonance excitation (curves II) [31] is in good agreement with both the measured  $R_{\text{AA}}$  and  $v_2$ . This is achieved with a small heavy quark relaxation time  $\tau$  which translates into a diffusion coefficient  $D_{\text{HQ}} \times (2\pi T) = 4-6$  in this model [31]. Energy loss and flow are also calculated in [32] in terms of  $D_{\text{HQ}}$  (curves III). While this model fails to simultaneously describe the measured  $R_{\text{AA}}$  and  $v_2$  with one value for  $D_{\text{HQ}}$ , the range for  $D_{\text{HQ}}$  leading to reasonable agreement with  $R_{\text{AA}}$  or  $v_2$  is similar to that from [31], again implying that small  $\tau$  and/or  $D_{\text{HQ}} \times (2\pi T)$  are required to reproduce the data. Note that  $D_{\text{HQ}}$  provides an upper bound for the bulk matter's diffusion coefficient  $D$ . Using the observation [32] that  $D \approx 6 \times \eta/(\epsilon + p)$  with  $\epsilon + p = Ts$  at  $\mu_B = 0$  provides an estimate for the viscosity to entropy ratio  $\eta/s \approx (\frac{4}{3} - 2)/4\pi$ , intriguingly close to the conjectured quantum lower bound  $1/4\pi$  [33]. This result is consistent with estimates obtained in the light quark sector from elliptic flow [34] and fluctuation analyses [35].

The conjecture of a bound on  $\eta/s$  [16] was obtained using the anti-de Sitter-space/conformal-field-theory correspondence [36,37], which exploits a duality between strongly coupled gauge theories and semiclassical gravitational physics. Recently, such methods were applied to estimate  $\hat{q}$  [38] and  $D_{\text{HQ}}$  in a thermalized plasma [39-41]. These authors also find a small diffusion coefficient  $D_{\text{HQ}} \times (2\pi T) \sim 1$ .

In conclusion, we have observed large energy loss and flow of heavy quarks in Au + Au collisions at  $\sqrt{s_{\text{NN}}} = 200$  GeV. The data provide strong evidence for the coupling of heavy quarks to the produced medium. A short relaxation time of heavy quarks and/or a small diffusion coefficient are required by the data. A model comparison suggests a viscosity to entropy ratio of the medium close to the quantum lower bound, i.e., near a perfect fluid.

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