Elliptic flow of non-photonic electrons in Au+Au collisions at $\sqrt{s_{NN}} = 200, 62.4$ and 39 GeV

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We present the measurements of elliptic flow ($v_2$) of non-photonic electrons (NPE) by the STAR experiment using 2- and 4-particle correlations, $v_2^2$ and $v_2^4$, and the event plane method in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and $v_2^2$ at 62.4 and 39 GeV. $v_2^2$ and $v_2^4$ are non-zero at low and intermediate transverse momentum ($p_T$) at 200 GeV, and $v_2^2$ is consistent with zero at low $p_T$ at other energies. For Au+Au collisions at $p_T < 1$ GeV/$c$, there is a statistically significant difference between $v_2^2$ at 200 GeV and $v_2^2$ at the two lower beam energies.
INTRODUCTION

Experiments of ultrarelativistic heavy-ion collisions aim to create deconfined nuclear matter, a Quark-Gluon Plasma (QGP), and to study the QGP properties. Among the signatures of creation of a QGP is the number-of-constituent-quark scaling of elliptic flow of light and strange hadrons produced in the collisions, indicating partonic collectivity [1]. Elliptic flow is defined as the second harmonic \( v_2 \) (in the Fourier expansion of the particle azimuthal anisotropic distribution with respect to the reaction plane, \( \Psi_{\text{RP}} \) [2]):

\[
\frac{d^2N}{dp_T d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos(n(\phi - \Psi_{\text{RP}})),
\]

where \( \phi \) and \( p_T \) represent the azimuthal angle and the transverse momentum of the particle, respectively. The reaction plane contains the impact parameter and the beam momenta. In practice, the estimated reaction plane is called the event plane.

Heavy quarks provide a unique probe of the QGP properties: because their masses are large compared with the thermal energy expected in heavy-ion collisions [3], they are mainly produced in interactions with high momentum transfer, very early in the heavy-ion collisions, and they are expected to interact with the QGP differently than light and strange quarks [4-6]. Moreover, the heavy quark production is sensitive to the dynamics of the nuclear medium created in the collisions [7]; measurements of their production and elliptic flow could be used to determine the fundamental properties of the QGP, such as transport coefficients (see, for instance, Ref. [8] and references therein).

Electrons from the semileptonic decays of heavy flavor mesons (also called non-photonic electrons, NPE) represent well the directions of the mother D (B) mesons, especially when electron \( p_T > 1.5(3) \text{ GeV/c} \). Thus NPE \( v_2 \) serves as a proxy for heavy quark \( v_2 \).

In this paper, we present the STAR measurements of NPE \( v_2 \) using the two- and four-particle correlations \( \{v_2(2) \text{ and } v_2(4), \text{ respectively} \} \) and the event plane method \( \{v_2(\text{EP})\} \) in Au+Au collisions at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \) at the Relativistic Heavy Ion Collider (RHIC). These approaches have different sensitivities to elliptic flow fluctuations and to particle correlations not related to \( \Psi_{\text{RP}} \), so called non-flow. Jets and resonance decays are considered to be the most important sources of these non-flow correlations.

In the case of \( v_2(2) \) and \( v_2(\text{EP}) \), there are positive contributions from both \( v_2 \) fluctuations and non-flow (the event plane and two-particle correlation methods are approximately equivalent [11]). When \( v_2 \) is obtained with four-particle correlations \( \{v_2(4)\} \), the fluctuations give a negative contribution and the non-flow is suppressed. Therefore, \( v_2(2) \) gives an upper limit, and \( v_2(4) \) gives a lower limit, on elliptic flow [12].

We also present NPE \( v_2(2) \) in Au+Au collisions at \( \sqrt{s_{\text{NN}}} = 62.4 \text{ and } 39 \text{ GeV} \). RHIC Beam Energy Scan results show that elliptic flow of inclusive charged hadrons is approximately independent of beam energy in this energy range (the difference is less than 10% for \( 0.5 < p_T < 3 \text{ GeV/c} \)) [13]. Measurements of NPE \( v_2(2) \) at these energies could provide information about energy dependence of the strength of heavy quarks interactions with a hot and dense nuclear medium.

DATA ANALYSIS

Three main STAR subsystems are used in this analysis: the Time Projection Chamber (TPC) [14], Barrel Electromagnetic Calorimeter (BEMC) [15] and Time-of-Flight (ToF) [16] detectors. These detectors provide tracking and particle identification. We use events with minimum-bias and high \( p_T \) (so called high tower) triggers with primary vertices located within ±30 cm of the TPC’s geometrical center along the beam direction. We select tracks with at least 20 points measured in the TPC and at least 52% of the maximum number of possible TPC points. The distance-of-closest-approach (DCA) of a track to the collision vertex is required to be less than 1.5 cm. Collision centrality is determined using the number of reconstructed tracks in the TPC within \( |\eta| < 0.5 \) [13]. Events with 0-60% centrality are selected for the \( v_2 \) measurement; however, we use minimum-bias events (0-80% centrality) to increase statistics in the electron purity estimation. The data samples used in this study are summarized in Tab. [1].

Electrons are identified using the ionization energy loss \( (dE/dx) \) in the TPC, the time-of-flight in the ToF detector and the energy deposited in BEMC towers. First, we select tracks with \( |\eta| < 0.7 \) and \( 0 < n\sigma_{\text{electron}} < 3 \), where \( n\sigma_{\text{electron}} \) is the number of standard deviations from the expected mean \( dE/dx \) for electrons in the TPC. The \( n\sigma_{\text{electron}} \) cut was chosen to optimize the purity (to reduce a potential systematic error due to hadron contamination) and the available statistics (which is crucial for the \( v_2(4) \) measurement). For \( p_T < 1 \text{ GeV/c} \), the velocity \( \beta \) measured in the ToF is used to reject kaons: we require \( |1 - 1/\beta| < 0.03 \) at 200 GeV, \( -0.03 < 1 - 1/\beta < 0.02 \) at 62.4 GeV and \( -0.03 < 1 - 1/\beta < 0.01 \) at 39 GeV. Different cuts are used because of the slightly different ToF resolution at different energies. To further enhance electron identification at 39 and 62.4 GeV, we impose a more stringent requirement on \( n\sigma_{\text{electron}} \) \( (0 < n\sigma_{\text{electron}} < 2) \) for these collision energies. In the \( p_T \) range where the proton \( dE/dx \) band overlaps with the electron band \( (1 < p_T < 1.5 \text{ GeV/c}) \), we apply an additional cut
of $|1 - 1/\beta| < 0.1$ in order to reduce proton contamination. Finally, at $p_T > 1$ GeV/$c$, we select tracks that have a momentum-to-energy ratio in the range of $0.3 < p_{CE}/E < 2$, where $E$ is the energy of a single BEMC tower associated with a TPC track. The BEMC has a Shower Maximum Detector (SMD), which is a proportional gas chamber with strip readout at a depth of five radiation lengths designed to measure shower shapes and positions in the $\eta - \phi$ plane, and used to discriminate between electrons and hadrons. In order to further improve the purity of the electron sample, we require tracks to occupy more than one strip in both $\phi$ and $\eta$ SMD planes.

| Collision energy | Data sample (million events) |
|------------------|-----------------------------|
| 200 GeV (minimum bias) | 150 |
| 200 GeV (high tower) | 41 |
| 62.4 GeV (minimum bias) | 38 |
| 39 GeV (minimum bias) | 81 |

TABLE I. Data samples used for the analysis.

Hadron contamination is estimated by first fitting a sum of Gaussian functions for charged hadrons and electrons to the $n_{\text{e}}^{\text{electron}}$ distribution in narrow $p_T$ bins. Figure 1 shows examples of such fits for the $0.7 < p_T < 0.8$ GeV/$c$ and $3 < p_T < 6$ GeV/$c$ bins for 62.4 GeV data. There is also a Gaussian for merged pions that arise from track merging due to the finite two-track resolution of the TPC; these have a $dE/dx$ distribution well (see Fig. 1(b)). To improve fitting in the ranges where the purity of the electron sample and hadrons, we use the ToF at low and intermediate $p_T$ to select tracks with a mass close to the mass expected for that specific hadron. At high $p_T$ ($p_T > 3$ GeV/$c$), pions and protons from $K^0_S$ and $\Lambda$ decays are selected, which are identified via reconstructed mass peaks in the $\eta - \phi$ plane. At this high $p_T$ range a simplified fit model (three Gaussian functions: for electrons, pions and protons combined with kaons) describes the $n_{\text{e}}^{\text{electron}}$ distribution well (see Fig. 1(b)). To improve fitting in the ranges where the $K^0_S$ and $\Lambda$ decays overlap with the electron band, we impose constraints on the hadron amplitudes: the amplitude of a Gaussian for a hadron there is limited by the values determined outside of that cross-over range, where hadron-electron separation is feasible. These fits are then used to calculate the hadron yields within the $n_{\text{e}}^{\text{electron}}$ range selected for the analysis. Purity is defined as a ratio of electrons to all tracks that passed the quality and electron identification cuts. Figure 2(a) shows the purity as a function of $p_T$; the overall purity is $90\%$ or better. Hadron contamination is only significant at 200 GeV for $p_T \sim 0.5 - 0.6$ GeV/$c$ and $p_T \sim 0.8 - 1.1$ GeV/$c$ due to the overlap of the kaon and the proton $dE/dx$ bands with the electron band, and the slightly more relaxed cuts used for that data set.

The primary source of physical background for this analysis are so-called photonic electrons. These electrons originate from real photon conversion in the detector material or from Dalitz decay of light mesons (mostly $\pi^0$ and $\eta$). We identify photonic electrons using a statistical approach, as a signal in the low mass region of the di-electron $m_{e+e-}$ mass spectrum (mass $m_{e+e-} < 0.15$ GeV$/c^2$) [17]. Each primary photon electron candidate is paired with an opposite-sign electron (so-called partner) in an event. We estimate the combinatorial background in this procedure with like-sign pairs. Figure 2(b) shows an example of an $m_{e+e-}$ distribution for minimum-bias Au+Au 62.4 GeV events. The photonic electron yield is calculated by $N_{\text{pho}} = (N_{\text{UL}} - N_{\text{LS}})/\varepsilon_{\text{pho}}$, where $N_{\text{UL}}$ and $N_{\text{LS}}$ are the numbers of unlike-sign and like-sign electron pairs, respectively. $\varepsilon_{\text{pho}}$ is the partner finding efficiency (also called the photon electron reconstruction efficiency) which we determine from full GEANT simulations of the STAR detector. Figure 2(c) shows $\varepsilon_{\text{pho}}$ as a function of $p_T$; it varies from 15% at 0.5 GeV/$c$ to 60% at 7 GeV/$c$.

The “raw” non-photonic electron signal, $N_{\text{NPE}}$, is given by $N_{\text{NPE}} = pN_f - N_{\text{pho}}$, where $N_f$ is the inclusive electron sample and $p$ is the purity. Besides photonic electrons, other sources of background in this analysis are weak kaon decay ($K^+ \rightarrow e^+\nu\pi^0$ and $K^0_L \rightarrow e^+\nu\pi^0$), called $K_{e3}$, quarkonia and other vector mesons [17]. $K_{e3}$ is the largest source of that secondary background and we subtract it from our non-photonic electron sample, as described later in this section.

Figure 3 shows the non-photonic electron signal (with $K_{e3}$ background subtracted) to photon electron background ratio for Au+Au 200, 62.4 and 39 GeV. This ratio varies from 0.3 at low $p_T$ to 1.4 at $p_T$ above 5 GeV/$c$; overall, it is lower at 62.4 and 39 GeV compared to 200 GeV because the cross-section for heavy quark production decreases faster with decreasing colliding energy than does the cross-section for the photon electron background.

To determine the non-photonic electron elliptic flow, we first measure inclusive electron $v_2$, photon electron $v_2$ and hadron azimuthal anisotropy and their yields. Then the $v_2^{\text{NPE}}$ is given by

$$v_2^{\text{NPE}} = \frac{N_E v_2^E - N_{\text{pho}} v_2^{\text{pho}} - N_H v_2^H}{N_{\text{NPE}}}$$

(2)

where $N_H = (1 - p)N_f$ is the hadron contamination, $v_2^E$ the inclusive electron elliptic flow and $v_2^H$ the hadron azimuthal anisotropy. $v_2^H$ is calculated as the sum of $v_2$ for different particle species [19,21] weighted by their yields in the inclusive electron sample. These yields are estimated based on the purity studies. Elliptic flow of
these components (inclusive and photonic electrons and hadrons) can be measured using any method (for instance $v_2\{2\}$, $v_2\{4\}$ or $v_2\{\text{EP}\}$).

In the $v_2\{2\}$ and $v_2\{4\}$ analyses, we obtain $v_2^I$ and $v_2^H$ directly from the data. Inclusive electron $v_2\{2\}$ and $v_2\{4\}$ are calculated using the direct cumulant method Ref. 22: for $v_2\{2\}$ we correlate an electron with a single hadron, while one electron is correlated with three hadrons for $v_2\{4\}$. We calculated the reference flow using tracks with $0.2 < p_T < 2 $ GeV/c within $|\eta| < 1$, excluding tracks with $|n\sigma_{\text{electron}}| < 3$ to avoid self-correlations. The results are corrected for non-uniform azimuthal detector acceptance by applying the procedure described in Ref. 22. $v_2^{\text{pho}}$ is given by GEANT simulations of electrons from $\gamma$ conversions and $\pi^0$ and $\eta$ Dalitz decays, where the measured parent $v_2(\text{pt})$ and $p_T$ spectra are required as an input. Direct photon $v_2$ and $p_T$ spectra at 200 GeV are taken from Refs. 23-25. For Au+Au 62.4 and 39 GeV, there are no published data available; therefore, we use results for $p$ and assume binary scaling of the direct photon yield. We use NLO pQCD calculations for $p+p$ at 62.4 GeV Refs. 26-27 and E706 data for 39 GeV Refs. 28. We use the $v_2(p_T)$ ($v_2\{2\}$ and $v_2\{\text{EP}\}$) and $p_T$ spectra for neutral and charged pions measured by STAR and PHENIX as input for the simulation Refs. 18-19,29-32, and we assume $m_T$ scaling for $\eta$.

In the event-plane analysis, we reconstruct an event-plane using tracks with $0.15 < p_T < 1.5 $ GeV/c and $|\eta| < 1$ in order to reduce the effect of jets on the event plane estimation. We exclude tracks with $|n\sigma_{\text{ electron}}| < 3$ to avoid possible self-correlations between the particle of interest (the electron) and tracks used in the event plane reconstruction. The results are corrected for non-uniform detector acceptance using $\phi$ weighting and event-by-event shifting of the planes, which is needed to make the final distribution of the event planes isotropic Refs. 18-19. We obtain $v_2^{\text{NPE}\{\text{EP}\}}$ directly from the data: we measure the NPE production differentially at all azimuthal angles with respect to the event plane and fit the distribution with $dN/d\Delta\phi = A \times [1 + 2 v_2^{\text{NPE}\{\text{EP}\}} \cos(2\Delta\phi)]$, where $\Delta\phi \equiv \phi - \Psi_{\text{EP}}$ is the particle azimuthal angle with respect to the event plane $\Psi_{\text{EP}}$, reconstructed event by event. The observed $v_2\{\text{EP}\}$ coefficients are corrected for the finite event plane resolution, which is estimated from the correlation of the planes of independent sub-events Ref. 10.

The $K_{\text{e3}}$ contribution is estimated using a full GEANT simulation of the STAR detector for both $K^0_L$ and charged kaons. We use the $K^0_S$ $p_T$ spectra measured by STAR as an input in these simulations. The efficiency for $K_{\text{e3}}$ reconstruction is very low at low $p_T$ due to a DCA cut applied in the analysis: 2% at $p_T = 0.5 $ GeV/c and 5% at $p_T = 1 $ GeV/c. We compared the $K_{\text{e3}}$ background to the expected heavy flavor electron yield taking into account the single electron reconstruction efficiency and acceptance. In the case of Au+Au 200 GeV, we use the NPE spectra measured by PHENIX Refs. 33 as an input. For Au+Au 39 and 62.4 GeV, the NPE $p_T$ spectrum is not available and we use a perturbative QCD prediction for NPE production Refs. 34 scaled by the number of binary collisions. The NPE measurements in $p+p$ at $\sqrt{s_{\text{NN}}} = 200$ GeV are consistent with the upper limit of the pQCD calculation; therefore, we use the upper limit on the predictions as an estimate of NPE yield at lower energies. The $K_{\text{e3}}$ electron background is small at 200 GeV and it decreases with increasing $p_T$: we estimate it to be 8% for $p_T < 1 $ GeV/c and less than 2% for $p_T > 3 $ GeV/c. However, the heavy quark production cross-section decreases faster with decreasing energy than does the cross-section for strangeness production. Thus the relative $K_{\text{e3}}$ electron background is larger at 39 and 62.4 GeV than at the top RHIC energy: it amounts to $\approx 30\%$ for $p_T < 0.5 $ GeV/c and $\approx 10\%$ for $0.5 < p_T < 3 $ GeV/c at 62.4 GeV. It is even higher at 39 GeV: $\approx 50\%$ for
\( \text{FIG. 2. (Color online) Electron purity (a), electron pair invariant mass distribution for electrons with } 0.8 < p_T < 8.5 \text{ GeV/c (b), and photonic electron reconstruction efficiency (c). The bands show combined systematic and statistical errors. Centrality classes are indicated in the plot.} \)

\( p_T < 0.5 \text{ GeV/c and } \approx 20\% \text{ for } 0.5 < p_T < 3 \text{ GeV/c.} \)

We calculate the \( K_{\text{e3}} v_2 \) using a GEANT simulation of the STAR detector taking as input the kaon \( p_T \) spectrum and \( v_2 \) measured by STAR. The expected \( K_{\text{e3}} p_T \) spectrum and \( v_2 \) are then subtracted from the measured non-photonic electron yield and \( v_2 \).

\( \text{FIG. 3. (Color online) Signal-to-background ratio for non-photonic electrons at } \sqrt{s_{NN}} = 200, 62.4 \text{ and } 39 \text{ GeV. The error bars represent the statistical uncertainty, and the brackets represent the systematic uncertainties. See text for details.} \)

There are three dominant sources of systematic uncertainties in this analysis: the photonic electron reconstruction efficiency, the purity and the input parameters to the photonic electron \( v_2 \) simulation. We estimate the systematic error on \( \varepsilon_{\text{pho}} \) by varying the contribution of direct photons to the photonic electron yield, and by comparing the partner finding efficiency in the simulations and the data. The overall systematic error on \( \varepsilon_{\text{pho}} \) is \( \pm 7\% \) at 200 GeV, \( \pm 8\% \) at 62.4 GeV and \( \pm 10\% \) at 39 GeV. The systematic error on the purity is estimated by varying the constraints in a multi-Gaussian fit. These uncertainties vary strongly with \( p_T \): Fig. 2(a) shows the purity with the combined systematic and statistical errors. The uncertainty on the photonic electron \( v_2 \) is evaluated by varying the input spectra within their statistical and systematic errors, and varying the relative contributions of the simulation components. We estimate the systematic error on the \( K_{\text{e3}}/\text{NPE} \) ratio by varying the input NPE distribution. At 200 GeV, we vary the input spectra within statistical and systematic errors; at 39 and 62.4 GeV, we use a central value of pQCD predictions as an estimate of the lower limit on the NPE production. The overall error on photonic electron \( v_2 \) is 6\% for \( p_T < 5 \text{ GeV/c; for } 200 \text{ GeV at high } p_T \), it increases with \( p_T \) to 20\% at \( p_T = 7 \text{ GeV/c.} \)

\textbf{RESULTS}

Figure 4 shows the inclusive and photonic electron \( v_2(2) \) and \( v_2(4) \) for the 0-60\% most central Au+Au collisions at 200, 62.4 and 39 GeV. The photonic electron \( v_2 \) is larger than the inclusive electron \( v_2 \) at low and intermediate \( p_T (p_T < 4 \text{ GeV/c}) \), which indicates that the NPE \( v_2 \) has to be smaller than \( v_2' \). Figure 5 shows the
non-flow in Au+Au can be estimated by taking the average two-particle correlation of NPE and hadrons in p+p for \( p_T > 0.5 \text{ GeV/c} \) at 200 GeV. If we assume that non-flow correlations in p+p are similar to those in Au+Au, similarly to Ref. \( [36] \). If we assume that non-flow correlations in Au+Au, similarly to Ref. \( [36] \), the non-flow at \( s_{NN} = 200 \text{ GeV} \) is the average two-particle correlation of NPE–hadron correlations \( \langle \langle p_{h}^\prime \rangle \rangle \) for \( p_T > 4 \text{ GeV/c} \), which is probably an effect of jet-like correlations. We estimate the strength of these correlations for \( p_T > 2.5 \text{ GeV/c} \) using NPE–hadron correlations in p+p at \( \sqrt{s} = 200 \text{ GeV} \) \( [35] \): the non-flow correlations in p+p are scaled by hadron multiplicity in Au+Au, similarly to Ref. \( [36] \). If we assume that non-flow correlations in p+p are similar to those in Au+Au, then the non-flow in Au+Au can be estimated by

\[
    v_2^{\text{non-flow}} = \frac{\langle \langle 2' \rangle \rangle_{pp}}{v_2(2)_{pp}} \frac{\langle N_{h}^{pp} \rangle}{\langle N_{h}^{AA} \rangle},
\]

where \( \langle \langle 2' \rangle \rangle_{pp} \) is the average two-particle correlation of NPE and hadrons in p+p, \( \langle N_{h}^{pp} \rangle \) and \( \langle N_{h}^{AA} \rangle \) is the aver-
We quantify the difference using significantly from the trend seen at top RHIC energy. \(v_2\) to overlap (consistent with STAR results in the \(p\bar{p}\) decays on the detector used for electron identification is expected to reduce the effect of jet-like correlations and resonance decays between the BBCs and the pseudorapidity gap representing combined statistical uncertainties and systematic uncertainties due to electron identification and photonic electron rejection [35]. Those certainties and systematic uncertainties due to electron identification and photonic electron rejection [35] are compared to the PHENIX measurement. The difference between results at 200 and 39 GeV, \(\chi^2/\text{NDF} = 10.5/2\) which corresponds to \(p = 0.005\). Thus the null hypothesis is rejected at \(\alpha = 0.01\) and the difference between \(v_2\) at 200 and 62.4 GeV and 39 GeV for \(p_T < 1\) GeV/c is statistically significant.

The observed \(v_2\) for NPE is modified with respect to the parent quark \(v_2\) due to the decay kinematics of the parent heavy hadron. This effect is shown in Fig. 6 by predictions for heavy quark elliptic flow and the resulting electron \(v_2\) from partonic transport model BAMPS [37, 38]. Also, the NPE \(p_T\) spectrum is shifted towards lower \(p_T\) compared to the parent hadron spectra, which makes the interpretation of the NPE data model-dependent. Figure 6 shows NPE \(v_2\{2\}\) and \(v_2\{4\}\) at 200 GeV compared to a few models of heavy quark interactions with the partonic medium, which are described below. Note, that all models here calculate the elliptic flow of NPE and heavy quarks with respect to the reaction plane. The flow fluctuations and non-flow are not included there, therefore the predicted \(v_2\) values should be between \(v_2\{2\}\) and \(v_2\{4\}\). Unfortunately, limited statistics do not allow us to quantify this difference in the data – the measured \(v_2\{4\}\) is consistent with \(v_2\{2\}\) within errors.

In a partonic transport model, BAMPS [37, 38] (blue dash-dotted line), heavy quarks lose energy by collisional energy loss with the rest of the medium. To account for radiative energy loss, which is not implemented in this model, the heavy quark scattering cross-section is scaled up by a phenomenological factor, \(K = 3.5\). In BAMPS, the hadronization is implemented as fragmentation into \(D\) and \(B\) mesons using the Peterson function. Thus the observed finite \(v_2\) of non-photonic electrons comes only from the elliptic flow of charm quarks. Indeed, heavy quarks have a large elliptic flow in this model (dotted line). Note that the Peterson fragmentation is not an appropriate description of hadronization at low \(p_T\) and other, more sophisticated mechanisms (for instance, coalescence) should be implemented. Overall, BAMPS describes \(v_2\{2\}\) data well, but it slightly underestimates the nuclear modification factor \(R_{AA}\) for heavy flavor electrons, reported by PHENIX, at intermediate \(p_T\) (1.5 < \(p_T\) < 4 GeV/c) [38]. It has been shown in Ref. [39] that initial-state parton-\(k_T\) broadening (also called the Cronin effect) increases the predicted \(R_{AA}\) in a \(p_T\) range of 1 - 3 GeV/c and improves the agreement with the data. However, it has almost no effect at high \(p_T\) and thus it is not important for the energy loss studies.

The dash-dotted green line shows the implementation of radiative and collisional energy loss from Gossiaux et
elliptic flow of light quarks alone cannot account for the meson elliptic flow. In general, coalescence is expected to deliver such data in the next few years. Vor Tracker and the Muon Telescope Detector [45], will two new STAR detectors, the Heavy Flavor Tracker and the Muon Telescope Detector [45], will advance our understanding of the partonic medium to a simultaneous comparison with other experimental trends of the data. To further discriminate between models, a coalescence approach in the shown pT range, while in the BAMPS model heavy quarks fragment into mesons. In general, coalescence is expected to give a larger v2 of the mesons due to the contribution of the light quark flow. However, it is shown in [33, 44] that elliptic flow of light quarks alone cannot account for the observed NPE v2. In that model, the data are approximately reproduced if charm quarks have an elliptic flow similar to that of light quarks.

The theoretical models discussed here, despite the different mechanisms employed, assume that charm quarks are strongly coupled with the medium and have a finite elliptic flow. All these models qualitatively follow the trend of the data. To further discriminate between models, a simultaneous comparison with other experimental observables (nuclear modification factor, azimuthal correlations) as a function of beam energy is required. Our v2(2) measurements at 39 and 62.4 GeV provide such additional benchmarks for testing hypotheses of heavy quark energy loss. Moreover, precision measurements of these quantities for charmed and bottom hadrons separately are necessary to further constrain models and to advance our understanding of the partonic medium properties. Two new STAR detectors, the Heavy Flavor Tracker and the Muon Telescope Detector [45], will deliver such data in the next few years.

**SUMMARY**

We report the first measurement of non-photonic electron azimuthal anisotropy using 2- and 4-particle correlations at √sNN = 200 GeV, and v2{2} at 62.4 and 39 GeV. NPE v2{2} and v2{4} are non-zero at low and intermediate pT at 200 GeV; more data is needed to quantify the effect of fluctuations and non-flow on the measured elliptic flow. At lower energies, the measured value of v2{2} is consistent with zero. The χ² tests for a consistency between v2{2} at √sNN = 200 GeV and lower energies for pT < 1 GeV/c give χ²/NDF = 13.2/2 for √sNN = 62.4 GeV, and χ²/NDF = 10.5/2 for √sNN = 39 GeV. These values correspond to probabilities of p = 0.0014 and p = 0.005, respectively. Thus the difference between v2{2} for pT < 1 GeV/c in Au+Au collisions at √sNN = 200 and v2{2} at the two lower beam energies is statistically significant.

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