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Resonance decay effects on anisotropy parameters

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Abstract

We present the elliptic flow v_2 of pions produced from resonance decays. The transverse momentum p_T spectra of the parent particles are taken from thermal model fits and their v_2 are fit under the assumption that they follow a number-of-constituent-quark (NCQ) scaling law expected from quark-coalescence models. The v_2 of pions from resonance particle decays is found to be similar to the measured pion v_2. We also propose the measurement of electron v_2 as a means to extract open-charm v_2 and investigate whether a thermalized system of quasi-free quarks and gluons (a quark–gluon plasma) is created in collisions of Au nuclei at RHIC.

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1. Introduction

One of the surprising observations made at RHIC is the measurement of a number-of-constituent-quark (NCQ) dependence for both elliptic flow v_2 and the nuclear modification factor R_{CP} at intermediate p_T ($1.5 < p_T < 5$ GeV/c) [1]. Models of hadron formation by constituent-quark coalescence provide a viable explanation for these observations whereas expectations based on conventional fragmentation approaches are inconsistent with the data [2–4]. In coalescence models an NCQ-scaling of v_2 arises as a consequence of hadrons coalescing out of a thermal distribution of partons and reveals the flow developed during a partonic epoch at RHIC. Pion v_2, however, appears to violate NCQ-scaling. In this Letter, we study the effect of resonance decays on pion v_2. We show that when decays are taken into account, the measured pion v_2 may become consistent with the NCQ-scaling demon-

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strated by kaon (K^+, K^-, K^0_S), proton, Λ, and Ξ v_2 [1,5].

The particle azimuthal distribution with respect to the reaction plane at rapidity y can be described by a Fourier expansion

$$\frac{dN}{d\Delta\phi} \propto 1 + \Sigma_n 2v_n \cos(n\Delta\phi), \tag{1}$$

where $\Delta\phi$ is the difference in azimuth angle between the particle and the reaction plane. The first and second Fourier coefficients, v_1 and v_2, historically are called directed and elliptic flow, respectively. All coefficients can be calculated from the relation: $v_n = \langle\cos(n\Delta\phi)\rangle$.

As the volume of the system created in an off-axis nucleus–nucleus collision expands, its spatial anisotropy quenches. The momentum-space anisotropies represented by the Fourier coefficients v_n preserve information about the early collision dynamics when the spatial anisotropy was largest [2,6–8]. Since the initial overlap region is elliptical in shape, the second harmonic coefficient v_2 is the largest and most studied.

2. NCQ-scaling of v_2

Fig. 1 shows the $\pi^+ + \pi^-$, K^0_S, $p + \bar{p}$, and $\Lambda + \bar{\Lambda}$ v_2 from minimum-bias ^{197}Au + ^{197}Au collisions at $\sqrt{s_{NN}} = 200$ GeV [1,5]. In the lower p_T region ($p_T < 1.0$ GeV/c), the values of v_2 are lower for higher mass hadrons. Hydrodynamic calculations [9] predict the observed mass dependence of v_2—perhaps implying that a thermalized system has been created in collisions at RHIC energy. At higher p_T ($p_T \geqslant 2$ GeV/c), the v_2 measurements saturate at values below the hydrodynamic model predictions. The saturated value of v_2 and the p_T scale where the saturation sets in depends on the particle-type: the baryon v_2 saturates at higher p_T and at larger values than that of mesons.

According to coalescence models [4], after scaling both v_2 and p_T with the number of the constituent quarks (NCQ) in the corresponding hadron, all particles at intermediate p_T should fall onto one universal curve. The NCQ-scaled v_2 measurements in Fig. 1(b) show that $v_2(p_T/n_q)/n_q$ for $p_T/n_q > 0.6$ GeV/c is similar for all particles *except* pions. This observation, coupled with the NCQ-dependence observed at intermediate p_T in the nuclear modification factor R_{CP} is evidence of hadron formation by coalescence or recombination. In this case, $v_2(p_T/n_q)/n_q$ represents a constituent quark momentum-space anisotropy v_2^q that arises as a consequence of collectivity in a partonic stage. Based on coalescence models, NCQ-scaling suggests the creation of a quark–gluon plasma (QGP) with v_2^q characterizing the properties of the QGP. For this reason, understanding the source of the discrepancy in the NCQ-scaled pion v_2 is imperative.

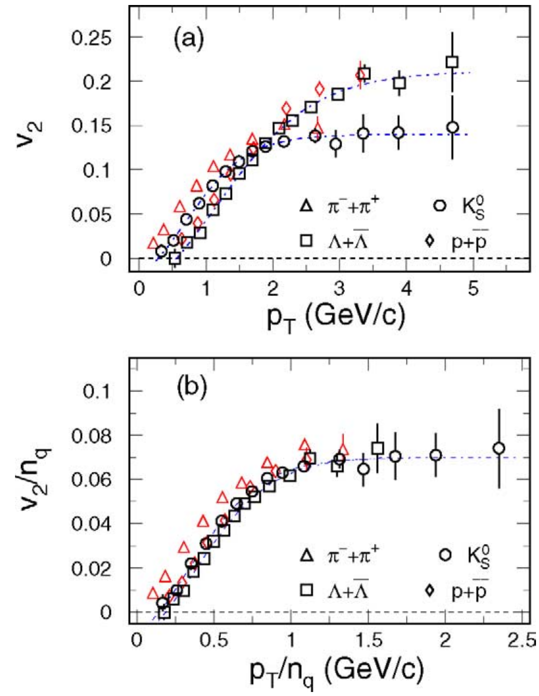

Fig. 1. (a) Measurements of the p_T dependence of the event anisotropy parameters for π, K^0_S, p, Λ. Dot-dashed lines are the results of fits. (b) Number-of-constituent-quark (NCQ) scaled v_2. All particles except the pions follow the NCQ scaling.

With this goal in mind, we study the effect of secondary pions (from particle decays) on the measured pion v_2. We assume that NCQ scaling is valid for all hadrons other than pions and use the published v_2 measurements [1,5] to parameterize $v_2(p_T/n_q)/n_q$. The p_T distributions are assumed to follow an exponential form with slope parameters taken from measurements when available. We use chemical fits to fix the relative hadron abundances [10,11]. Since the pion mass is much smaller than the sum of its constituent quarks masses, direct pions are not necessarily assumed to follow the scaling predicted from coalescence models. As such, we do not consider direct pions, and instead choose to study the v_2 of the secondary pions. Given the model uncertainties, extraction of the direct pion v_2 is difficult and remains an open question. Finally we will discuss how to extract open-charm v_2 based on the decayed electrons.

3. Simulation results

The v_2 values of the simulated resonances are parameterized by fitting K_S^0 and Λ v_2 [1] with the equation

$$f_{v_2}(n) = \frac{an}{1+\exp(-(p_T/n-b)/c)} - dn, \tag{2}$$

where a, b, c and d are the fit parameters, n is the constituent-quark number, and p_T is in the unit of GeV/c. The fit results are shown as dot-dashed lines in Fig. 1, where the fitting parameters are $a = 0.1$, $b = 0.35$, $c = 0.2$ and $d = 0.03$. The NCQ-scaling of v_2 works well for kaons, protons and Lambdas within $0.6 \leqslant p_T/n_q \leqslant 1.5$ GeV/c whereas pion v_2 deviates from NCQ scaling for all p_T. The parameters from chemical fits are listed in Table 1.

In high-energy collisions, a large fraction of hadrons are produced through resonance decays. This is particularly true for pions in high-energy heavy-ion collisions. At mid-rapidity, in collisions at RHIC, as many as 80% of pions are from resonance decays [12]. The dominant decays are $\rho \to \pi\pi$, $\omega \to 3\pi$, $K^*(892) \to K\pi$, $K_S^0 \to \pi\pi$ and $\Delta \to N\pi$. With such a potentially large fraction of pions arising from decays, accounting for their effect on the observed pion v_2 is very important.

The p_T distributions of pions from resonance decays are shown in Fig. 2. Many pions at low p_T are generated from resonances at larger p_T where presumably the parent particle v_2 is larger. As a result the decayed pions take on a relatively large v_2 value. The decays from the ρ- and ω-mesons dominate the secondary pion p_T spectrum. In this plot, a slope parameter of $T = 0.4$ GeV is used for the ρ distributions. In peripheral collisions, the STAR measured slope parameter is $319 \pm 4(\text{stat.}) \pm 32(\text{syst.})$ MeV [13]. The simulated results are in a good agreement with the PHENIX π^0 data from minimum bias $^{197}\text{Au} + {}^{197}\text{Au}$ collisions [14].

In Fig. 3, the v_2 values for the simulated decay pions are shown as dashed-lines. The resonances included in this study are the ρ, ω, K^*, K_S^0 and Δ. The decay $\rho \to \pi\pi$ with a 100% branching ratio dominates the production of secondary-pions. The simulated resonance particles are restricted to mid-rapidity $|y| < 0.5$. Increasing the rapidity window does not change the results. The pion v_2 in the region $p_T \leqslant 1.5$ GeV/c is sensitive to the shape of the ρ p_T spectrum. Dashed-, dotted-, and dot-dashed-lines correspond to the v_2 results from the different slope parameters listed in Table 1. For the smaller slope parameter $T = 300$ MeV, the decayed pion v_2 is below the data, leaving room for other contributions [15].

Table 1
Parameters for the input resonances: the units for slope parameters T are GeV. The fraction of the hadrons are fixed from the measured abundances

	$T1$	$T2$	$T3$	Fraction (%)
ρ	0.5	0.4	0.3	60 ± 10
ω	0.5	0.4	0.3	30 ± 10
K_S^0	0.3	0.3	0.3	6 ± 5
K^*	0.5	0.4	0.3	2 ± 1
Δ	0.55	0.55	0.55	2 ± 2

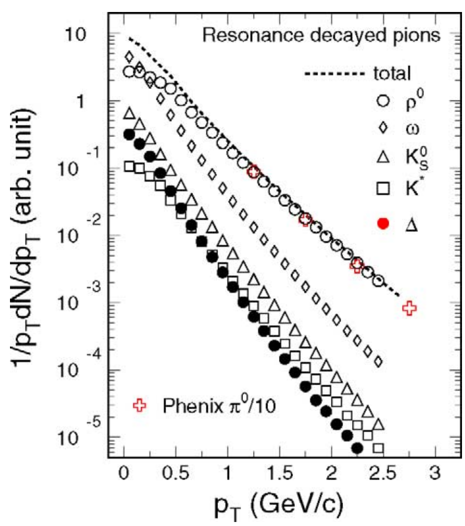

Fig. 2. Resonance decayed pion distributions. The summed spectrum is shown as a dashed-line. In this simulation, a slope parameter of $T = 0.4$ GeV is used for ρ, ω and K^*. For K_S^0 and Δ the respective slope parameters $T = 0.3$ GeV and 0.55 GeV are used. The relative fraction of the hadrons are listed in Table 1. For comparison, PHENIX π^0 results are shown as open-crosses.

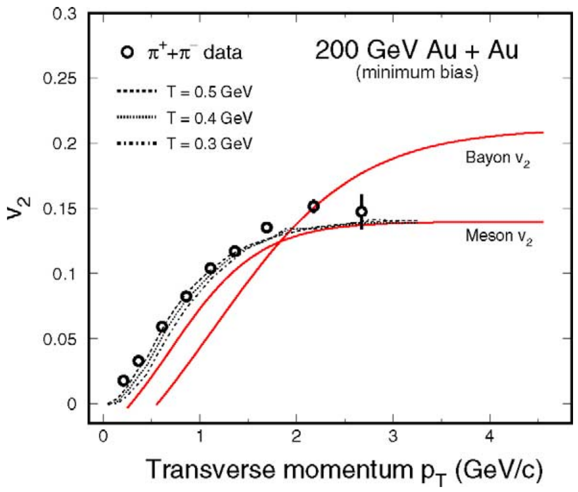

Fig. 3. The measured pion v_2 (symbols) is compared to the simulated v_2 for pions from resonance decays (dashed lines). The assumed v_2 of mesons and baryons are represented by the solid and dot-dashed lines, respectively.

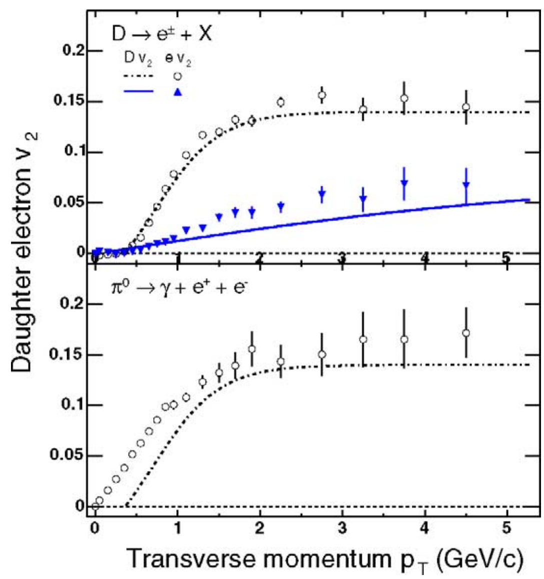

Fig. 4. The v_2 of electrons from D-meson decays (top) and π^0 decays (bottom). An input D-meson v_2 from a coalescence model with zero charm quark v_2 [17] is shown as a solid line (top). The input meson v_2 curve taken from our fit to the NCQ-scaled K_S^0 and $\Lambda+\bar{\Lambda}$ v_2 is shown as a dot-dashed line in both plots.

The effects of resonance decays on proton and kaon v_2 were also investigated. As in Ref. [15], they were found to increase the observed v_2 above the assumed NCQ-scaled input v_2 but by a much smaller degree than that of pions. Since the v_2 of kaons is used in our fits, resonance decays can change our assumed input v_2. These changes, however, will be small. In this Letter we concentrate on the pion v_2.

4. *D*-meson v_2

NCQ scaling suggests that hadrons at intermediate p_T are formed from a thermal partonic phase created in heavy-ion collisions at RHIC. In this system, the high initial matter density gradient and copious interactions among partons leads to a collective motion of partons. The large v_2 values measured for multi-strange hadrons also indicate that partonic collectivity develops in collisions at RHIC [16]. The demonstration of collectivity is necessary but not sufficient to show that local thermal equilibrium is established. If collectivity is developed by much heavier charm quarks, however, it suggests that interactions between charm quarks and u-, d-, or s-quarks must have been frequent enough and strong enough for the lighter quarks to have thermalized. For this reason, the measurement of heavy flavor (open-charm) v_2 can probe the degree to which the lighter u-, d-, and s-quarks thermalize.

Since a large fraction of heavy-flavor hadrons decay through leptonic modes, electron v_2 measurements may offer a convenient way to study open-charm v_2. In Fig. 4(top), the v_2 for electrons from D-meson decays is shown. Dot-dashed lines represent the v_2 of the parent meson taken from our fit to the NCQ-scaled K_S^0 and $\Lambda+\bar{\Lambda}$ v_2. The solid line represents a D-meson v_2 where D-mesons are assumed to coalesce from light quarks with $v_2^{u,d}>0$ and charm quarks with $v_2^c=0$ [17]. We simulate the D-meson p_T distribution using the PYTHIA event generator [18]. The shape of the calculated spectrum is well represented by a power-law function. Approximately 50 M D-meson events are used in this simulation. For electron $p_T>1.5$ GeV/c, and a saturated v_2 at higher p_T the v_2 of electrons from D-meson decays becomes similar to the parent D-meson v_2. The decay electron v_2 is found to be sensitive to changes in the assumed D-meson v_2. As such, the measurement of electron v_2 can distinguish between $v_2^c \approx v_2^{u,d}$ and $v_2^c \approx 0$. The degree of heavy flavor thermal equilibrium can be assessed by measuring electron v_2 within $1 \leqslant p_T(\mathrm{e}) \leqslant 3\ \mathrm{GeV}/c$, a region which corresponds to $2 \lesssim p_T(\mathrm{D}) \lesssim 5\ \mathrm{GeV}/c$. The authors of Ref. [19] come to a similar conclusion but do not evaluate background contributions to the electron spectrum.

Neutral pion decays are the dominant source of "background" electrons. While the two-photon decay process,

$$\pi^0 \xrightarrow{\sim 100\%} \gamma + \gamma \xrightarrow{\text{few}\%} e^+ + e^- + e^+ + e^-,$$

can be identified by its decay topology [20], the pion Dalitz decay can only be subtracted statistically. In Fig. 4(bottom) we show the v_2 of electrons from simulated pion Dalitz decays. The pion distribution can be obtained from measurements at RHIC [14]. For these simulations a 100% conversion probability is assumed. In STAR, however, the probability is closer to 5%. The decayed electrons predominantly have $p_T \leqslant 0.5\ \mathrm{GeV}/c$ [20].

Electrons from heavy flavor decays begin to dominate the electron spectrum above $p_T \sim 3\ \mathrm{GeV}/c$. With knowledge of the pion yield, D-meson yield, the pion v_2, and the electron v_2 it will be possible to extract the D-meson v_2. These measurements can be made by both the PHENIX and STAR Collaborations at RHIC. Direct photon v_2 can also be measured with this method.

5. Summary

We have studied the effect of resonance decays on the pion v_2 in Au + Au collisions at RHIC. When the v_2 values for resonances are assumed to follow NCQ scaling, the pions generated in their decays take on v_2 values similar to those measured at RHIC. The dominant source of secondary pions is ρ decays. We have shown that when decays are accounted for, the measured pion v_2 values *may* become consistent with the NCQ scaling law that suggests the development of partonic collectivity in collisions at RHIC. Model uncertainties, however, make it difficult to extract the direct pion v_2. In addition, we propose the measurement of electron v_2 as a means to study open-charm v_2 and hence the degree of thermalization reached at RHIC.

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References

[1] STAR Collaboration, J. Adams, et al., Phys. Rev. Lett. 92 (2004) 052302.
[2] S.A. Voloshin, Nucl. Phys. A 715 (2003) 379.
[3] R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, Phys. Rev. C 68 (2003) 044902.
[4] Z.W. Lin, C.M. Ko, Phys. Rev. Lett. 89 (2002) 202302;
R.J. Fries, B. Muller, C. Nonaka, S.A. Bass, Phys. Rev. Lett. 90 (2003) 202303;
D. Molnar, S.A. Voloshin, Phys. Rev. Lett. 91 (2003) 092301.
[5] PHENIX Collaboration, S.S. Adler, et al., Phys. Rev. Lett. 91 (2003) 182301.
[6] H. Sorge, Phys. Lett. B 402 (1997) 251.
[7] J.Y. Ollitrault, Phys. Rev. D 46 (1992) 229.
[8] N. Xu, Z.B. Xu, Nucl. Phys. A 715 (2003) 587.
[9] P. Huovinen, P.F. Kolb, U.W. Heinz, Nucl. Phys. A 698 (2002) 475;
P. Huovinen, P.F. Kolb, U.W. Heinz, P.V. Ruuskanen, S.A. Voloshin, Phys. Lett. B 503 (2001) 58.
[10] P. Braun-Munzinger, K. Redlich, J. Stachel, nucl-th/0304013, and references therein.
[11] N. Xu, M. Kaneta, Nucl. Phys. A 698 (2002) 306.
[12] Z.B. Xu, J. Phys. G 30 (2004) S325.
[13] STAR Collaboration, J. Adams, et al., Phys. Rev. Lett. 92 (2004) 092301.
[14] PHENIX Collaboration, S.S. Adler, et al., Phys. Rev. Lett. 91 (2003) 172301.
[15] V. Greco, C.M. Ko, nucl-th/0402020.
[16] STAR Collaboration, J. Adams, et al., Phys. Rev. Lett. 92 (2004) 182301.
[17] Z.W. Lin, D. Molnar, Phys. Rev. C 68 (2003) 044901.
[18] T. Sjöstrand, L. Lönnblad, S. Mrenna, hep-ph/0108264, and references therein.
[19] V. Greco, C.M. Ko, R. Rapp, nucl-th/0312100.
[20] STAR Collaboration, I.J. Johnson, Nucl. Phys. A 715 (2003) 691;
STAR Collaboration, J. Adams, et al., nucl-ex/0401008.