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Particle-type dependence of azimuthal anisotropy and nuclear modification of particle production in Au plus Au collisions at root s(NN)=200 GeV

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We present STAR measurements of the azimuthal anisotropy parameter v_2 and the binary-collision scaled centrality ratio $R_{\rm CP}$ for kaons and lambdas ($\Lambda + \overline{\Lambda}$) at midrapidity in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. In combination, the v_2 and $R_{\rm CP}$ particle-type dependencies contradict expectations from partonic energy loss followed by standard fragmentation in vacuum. We establish $p_T \approx 5$ GeV/c as the value where the centrality dependent baryon enhancement ends. The K_S^0 and $\Lambda + \overline{\Lambda}$ v_2 values are consistent with expectations of constituent-quark-number scaling from models of hadron formation by parton coalescence or recombination.

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The azimuthal anisotropy and system-size dependence of identified particle yields at moderate and high transverse momentum (p_T) may provide insight into the existence and properties of a deconfined partonic state in ultrarelativistic heavy-ion collisions [1–4]. The azimuthal anisotropy parameter v_2 is thought to be sensitive to the earliest stages of heavy-ion collisions [5]. The parameters v_n are derived from a Fourier expansion of the azimuthal component (ϕ) of the momentum-space distribution; $dN/d\phi \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_{RP})$, where Ψ_{RP} is the reaction-plane angle. Previous measurements at the Relativistic Heavy-Ion Collider (RHIC) established that v_2 for charged hadrons rises with p_T for $p_T < 2$ GeV/c and then saturates [6,7]. At low p_T ($p_T < 1$ GeV/c), the dependence of v_2 on particle mass [8,9] is consistent with hydrodynamic calculations where local thermal equilibrium of partons has been assumed [5,10,11].

Surface emission has been considered in relation to the large saturated v_2 at higher p_T [12]. The existence of a dense, opaque medium in which fast partons suffer energy loss can naturally lead to a surface emission pattern.

Parton energy loss in a dense medium may also suppress high p_T particle yields in central Au + Au collisions at RHIC [13]. High p_T particles are produced from initial hard parton scatterings whose cross sections are assumed to be proportional to the number of binary nucleon-nucleon collisions N_{bin}. The N_{bin} scaled centrality ratio R_{CP} is a measure of the particle production's dependence on the collision system's size and density:

$$R_{CP}(p_T) = \frac{[(dN/dp_T)/N_{bin}]^{Central}}{[(dN/dp_T)/N_{bin}]^{Peripheral}},$$

where $R_{CP} = 1$ if particle production is equivalent to a superposition of independent nucleon-nucleon collisions. In central Au + Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV, the moderate and high p_T neutral pion and charged hadron yields are suppressed relative to N_{bin} scaling (i.e., R_{CP} and the closely related nuclear modification factor R_{AA} are below unity) [14,15]. For $1 < p_T < 4.5$ GeV/c, the neutral pion yield is more strongly suppressed than the charged hadron yield, indicating a particle-type dependence for R_{CP}. Within the framework of parton energy loss followed by standard fragmentation, the suppression and v_2 both reflect the magnitude of the energy loss. The particle-type dependence of v_2 and R_{CP} will provide a stringent test for energy loss models.

Quark coalescence or recombination [1–4] models for hadron formation are an alternative to the fragmentation models commonly used in energy loss calculations [13]. In these models, a particle-type dependence develops at hadronization with baryons developing a larger v_2 and R_{CP} than mesons. In this Letter we present measurements of v_2 and R_{CP} at midrapidity ($|y| < 1$) for K^0_S and $\Lambda + \overline{\Lambda}$ for $0.2 < p_T < 6.5$ and $0.4 < p_T < 6.0$ GeV/c, respectively, along with R_{CP} for $K^{\pm}$ from $0.2 < p_T < 3.0$ GeV/c in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The K^0_S and $\Lambda + \overline{\Lambda}$ analysis extends the measurement of v_2 and R_{CP} for identified particles to a p_T range where previously only neutral pion R_{CP} had been measured and establishes the particle-type dependence of v_2 and R_{CP} at intermediate p_T (1.5–4.0 GeV/c) and high p_T ($p_T > 5$ GeV/c).

This analysis uses 1.6×10^6 minimum-bias trigger events and 1.5×10^6 central trigger events from the Solenoidal Tracker at RHIC (STAR) experiment [16]. The K^0_S and $\Lambda(\overline{\Lambda})$ were reconstructed from the topology of the decay channels, $K^0_S \rightarrow \pi^+ + \pi^-$ and $\Lambda(\overline{\Lambda}) \rightarrow p + \pi^-(\overline{p} + \pi^+)$. A detailed description of the analysis, such as track quality, decay vertex topology cuts, and detection efficiency, can be found in Refs. [9,17,18]. The $K^{\pm}$ are identified from one-prong decays as described in Ref. [19]. For both v_2 and R_{CP}, no difference is seen between Λ and $\overline{\Lambda}$ within statistical errors. The reaction-plane angle is estimated from the azimuthal distribution of primary tracks [20] with $0.1 < p_T < 2.0$ GeV/c and $|\eta| < 1.0$, where η is the pseudorapidity. To avoid autocorrelations, tracks associated with a K^0_S, Λ, or $\overline{\Lambda}$ decay vertex are excluded from the calculation of Ψ_{RP}.

Systematic errors in the calculation of v_2 are due to correlations unrelated to the reaction-plane (nonflow effects) and uncertainty in estimates of the background in the invariant mass distributions. Table I lists the dominant systematic errors. The systematic error in v_2 associated with the yield extraction (background) is found to be small and the nonflow systematic error is dominant. We estimate the nonflow contribution by comparing charged particle v_2 from a reaction-plane analysis and a four-particle cumulant analysis [6]. The four-particle cumulant analysis is thought to be insensitive to nonflow effects but leads to larger statistical errors. Any difference between the methods is assumed to arise from nonflow contributions. The nonflow contribution to v_2 has not been established experimentally for identified particles. We examined the effect of standard jet fragmentation on K^0_S and $\Lambda + \overline{\Lambda}$ v_2 using superimposed $p + p$ collisions generated with PYTHIA [21]. Within the measured p_T region, no significant differences are seen between $\Lambda + \overline{\Lambda}$ and K^0_S nonflow effects from this source. We assume a similar magnitude of nonflow contribution to $\Lambda + \overline{\Lambda}$ and K^0_S v_2 and use the difference between the charged particle v_2 from a reaction plane and a four-particle cumulant analysis to estimate the upper limit of possible nonflow contributions to both $\Lambda + \overline{\Lambda}$ and K^0_S v_2. Contributions to the systematic errors for R_{CP} come from the determination of

TABLE I. The relative systematic errors (%) from background (bg) and nonflow effects (nf) for v_2 (0–80%), and from background and the efficiency calculation (eff) for R_{CP} (0–5%/40–60%) are listed for three p_T values.

	K^0_S			$K^{\pm}$		$\Lambda + \overline{\Lambda}$		
p_T (GeV/c)	1.0	2.5	4.0	1.0	2.5	1.0	2.5	4.0
v_2 (bg)	+0	+1	+2			+2	+4	+2
	−1	−4	−10			−10	−1	−1
v_2 (nf)	+0	+0	+0			+0	+0	+0
	−15	−22	−20			−15	−22	−20
R_{CP} (bg)	±4	±2	±8	±2	±6	±2	±4	±6
R_{CP} (eff)	±10	±10	±10	±5	±9	±10	±10	±10

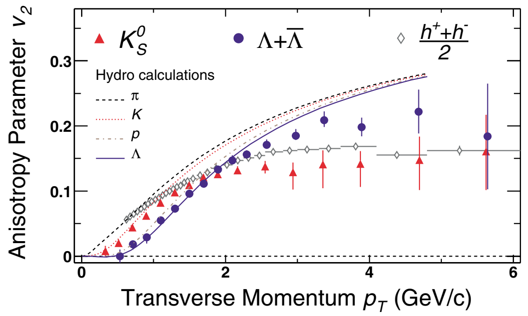

FIG. 1 (color online). The minimum bias (0%–80% of the collision cross section) $v_2(p_T)$ for K_S^0, $\Lambda + \overline{\Lambda}$, and $h^{\pm}$. The error bars shown include statistical and point-to-point systematic uncertainties from the background. The additional nonflow systematic uncertainties are approximately -20%. Hydrodynamical calculations of v_2 for pions, kaons, protons, and lambdas are also plotted [10].

the detector efficiency, extraction of the yields, and uncertainty in the model calculation of $N_{\rm bin}$ [15].

Figure 1 shows minimum bias v_2 for K_S^0, $\Lambda + \overline{\Lambda}$, and charged hadrons ($h^{\pm}$). The analysis method used to obtain the charged hadron v_2 is described in Ref. [7]. Figure 1 also shows hydrodynamic model calculations of v_2 for pions, kaons, protons, and lambdas [10]. At low p_T, v_2 is consistent with hydrodynamical calculations, in agreement with the previous results at $\sqrt{s_{NN}} = 130$ GeV [9]. This Letter establishes the particle-type dependence of the v_2 saturation at intermediate p_T. In contrast to hydrodynamical calculations, where at a given p_T heavier particles have smaller v_2 values, at intermediate p_T, $v_2^{\Lambda} > v_2^K$. The p_T scale where v_2 deviates from the hydrodynamical prediction is $\sim$2.5 GeV/c for $\Lambda + \overline{\Lambda}$ and $\sim$1 GeV/c for K_S^0.

Figure 2 shows v_2 of K_S^0 and $\Lambda + \overline{\Lambda}$ for three centrality intervals: 30%–70%, 5%–30%, and 0%–5% of the geometrical cross section. In each centrality bin, $v_2(p_T)$ rises at low p_T and saturates at intermediate p_T. The values of v_2 at saturation are particle type and centrality dependent.

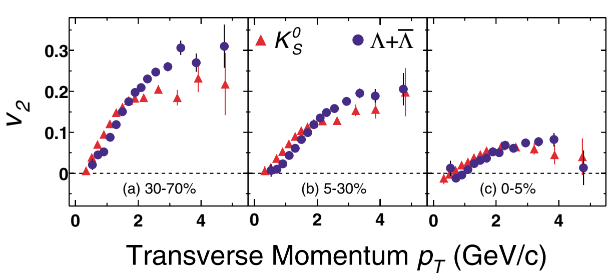

FIG. 2 (color online). The v_2 of K_S^0 and $\Lambda + \overline{\Lambda}$ as a function of p_T for 30%–70%, 5%–30%, and 0%–5% of the collision cross section. The error bars represent statistical errors only. The nonflow systematic errors for the 30%–70%, 5%–30%, and 0%–5% centralities are -25%, -20%, and -80%, respectively.

If partons that fragment into (anti-)lambdas lose more energy than those that fragment into kaons, a particle-type dependence for v_2 may develop at high p_T with $v_2^{\Lambda} > v_2^K$. In this case, $\Lambda + \overline{\Lambda}$ yields should be more suppressed than kaon yields. Figure 3 shows $R_{\rm CP}$ for K_S^0, $K^{\pm}$, and $\Lambda + \overline{\Lambda}$ using the 5% most central collisions, normalized by peripheral collisions (40%–60% and 60%–80%). For charged hadrons, these peripheral bins approximately follow $N_{\rm bin}$ scaling without medium modification [15]. The bands in Fig. 3 show the expected values of $R_{\rm CP}$ for binary and participant ($N_{\rm part}$) scaling including systematic variations from the calculation [15]. For most of the intermediate p_T region, $R_{\rm CP}$ for $\Lambda + \overline{\Lambda}$ is similar to expectations of $N_{\rm bin}$ scaling and $R_{\rm CP}^K < R_{\rm CP}^{\Lambda}$. The p_T scales associated with the saturation and reduction of $R_{\rm CP}$ also depend on the particle type. For both species, the p_T where $R_{\rm CP}$ begins to decrease approximately coincides to the p_T where v_2 in Fig. 1 saturates. At high p_T ($p_T > 5.0$ GeV/c), $R_{\rm CP}$ values for K_S^0 and $\Lambda + \overline{\Lambda}$ are consistent with the value for charged hadron $R_{\rm CP}$, indicating that the baryon enhancement observed at intermediate p_T in central Au + Au collisions ends at $p_T \approx 5$ GeV/c. The particle-type dependence of v_2 and $R_{\rm CP}$ at intermediate p_T are in contradiction to expectations from energy loss followed by fragmentation in vacuum.

Nuclear modifications such as shadowing and initial-state rescattering [22,23] may affect $R_{\rm CP}$ but they are not expected to give rise to such a large variation with particle type (e.g., [24]). At lower beam energy, the enhancement of yields in $p + A$ collisions at intermediate p_T (i.e.,

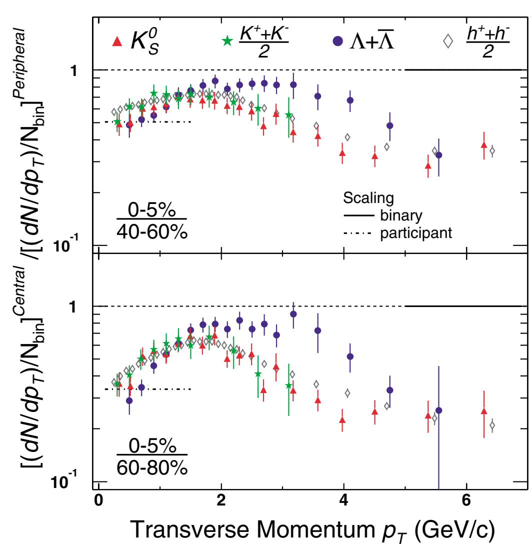

FIG. 3 (color online). The ratio $R_{\rm CP}$ for K_S^0, $K^{\pm}$, and $\Lambda + \overline{\Lambda}$ at midrapidity calculated using centrality intervals, 0%–5% vs 40%–60% (top panel) and 0%–5% vs 60%–80% of the collision cross section (bottom panel). The error bars shown on the points include both statistical and systematic errors. The widths of the gray bands represent the uncertainties in the model calculations of $N_{\rm bin}$ and $N_{\rm part}$. We also show the charged hadron $R_{\rm CP}$ measured by STAR for $\sqrt{s_{NN}} = 200$ GeV/c [15].

the Cronin effect [25]) is larger for baryons than mesons [22]. The Cronin effect has been attributed to initial-state rescattering and is expected to decrease with increasing beam energy [23]. Alternatively, a strong particle-type dependence of the Cronin effect may indicate a nuclear modification to the parton fragmentation. Although the effects of shadowing, initial-state rescattering, and nonflow deserve further investigation, the particle type and p_T dependence of v_2 and R_{CP} may reveal a crossover from a p_T region dominated by bulk partonic matter hadronization to one dominated by single parton fragmentation. Our measurements indicate that the crossover would occur at $p_T \sim 4$–5 GeV/c.

The larger $\Lambda + \overline{\Lambda}$ R_{CP} at intermediate p_T shows that the $\Lambda + \overline{\Lambda}$ yield increases with parton density faster than the kaon yield. Multiparton mechanisms such as gluon junctions [26], quark coalescence [2], or recombination [3] can naturally lead to a stronger dependence on parton density for baryon production than meson production. Models using coalescence or recombination mechanisms in particle production predict that at intermediate p_T v_2 will follow a number-of-constituent-quark scaling [2]. Figure 4 shows v_2 of K_S^0 and $\Lambda + \overline{\Lambda}$ as a function of p_T, where the v_2 and p_T values have been scaled by the number of constituent quarks (n). While v_2 is significantly different for K_S^0 and $\Lambda + \overline{\Lambda}$, within errors, v_2/n vs p_T/n is the same for both species above $p_T/n \sim 0.7$ GeV/c. In a scenario where hadrons at intermediate p_T coalesce from comoving quarks, $v_2/n(p_T/n)$ reveals the momentum-space azimuthal anisotropy of partons in a bulk matter [2].

At higher p_T where independent fragmentation is likely to dominate over multiparton particle production mechanisms, constituent-quark scaling is expected to break down and the K_S^0 and $\Lambda + \overline{\Lambda}$ v_2 may take on a value closer to that of an underlying partonic v_2 [2]. The convergence of K_S^0 and $\Lambda + \overline{\Lambda}$ R_{CP} at $p_T \sim 5$ GeV/c in Fig. 3 supports this expectation. Higher statistics v_2 measurements in this region along with measurements of v_2 for other identified particles will therefore provide an opportunity to test the scaling demonstrated in Fig. 4.

In summary, we have reported the measurement of v_2 and R_{CP} up to $p_T \sim 6.0$ GeV/c for kaons and $\Lambda + \overline{\Lambda}$ from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. At low p_T, hydrodynamic model calculations agree well with v_2 for K_S^0 and $\Lambda + \overline{\Lambda}$. At intermediate p_T, however, hydrodynamics no longer describes the particle production. For K_S^0, v_2 saturates earlier and at a lower value than for $\Lambda + \overline{\Lambda}$. The K_S^0 and $\Lambda + \overline{\Lambda}$ v_2 are shown to follow a number-of-constituent-quark scaling law. In addition, R_{CP} shows that the yield of $\Lambda + \overline{\Lambda}$ is increasing more rapidily with the system size than kaons: At intermediate p_T, the $\Lambda + \overline{\Lambda}$ R_{CP} is close to expectations from binary scaling while the kaon R_{CP} is lower. At high p_T, the R_{CP} of K_S^0 and $\Lambda + \overline{\Lambda}$ are consistent with the value for charged hadrons, indicating that the centrality dependent baryon enhancement observed at intermediate p_T ends near $p_T = 5$ GeV/c.

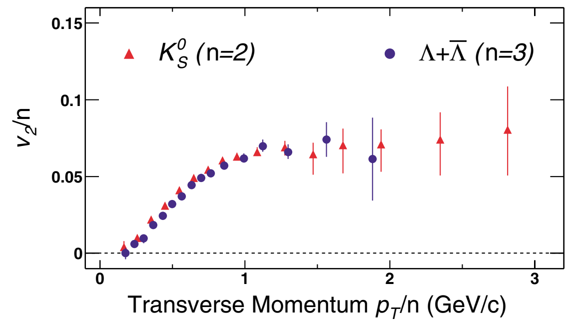

FIG. 4 (color online). The v_2 parameter for K_S^0 and $\Lambda + \overline{\Lambda}$ scaled by the number of constituent quarks (n) and plotted versus p_T/n. The error bars shown include statistical and point-to-point systematic uncertainties from the background. The additional nonflow systematic uncertainties are approximately −20%.

The measured features at intermediate p_T are consistent with the presence of multiparton particle formation mechanisms beyond the framework of parton energy loss followed by standard fragmentation. The particle dependence and p_T dependence of v_2 and R_{CP} constitute a unique means to investigate the anisotropy and hadronization mechanism of the bulk dense matter formed in nucleus-nucleus collisions at RHIC.

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