Particle dependence of azimuthal anisotropy and nuclear modification of particle production at moderate p_T in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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The elliptic flow parameter (v_2) and the centrality dependence of particle yields for kaons (K^0_S, K^+ and K^-) and lambdas ($\Lambda + \overline{\Lambda}$) have been measured at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR collaboration. A distinct particle-type dependence is observed within the measured p_T region ($p_T < 6$ GeV/c). At intermediate p_T, the $\Lambda + \overline{\Lambda}$ v_2 saturates at a higher value than the K^0_S v_2 and both deviate from the hydrodynamic type behavior observed in the low p_T region. The kaon yields in central collisions are suppressed with respect to expectations from binary scaling for all measured p_T. The yield of $\Lambda+\overline{\Lambda}$ in central collisions is close to expectations from binary scaling for p_T from 1.8–3.5 GeV/c. At $p_T \sim 5.0$ GeV/c, the K^0_S, $\Lambda + \overline{\Lambda}$ and charged hadron yields are suppressed from binary scaling by a similar factor. We discuss the physics implications of these features in the particle yields and v_2.

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Matter at extreme temperature and density is created in nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) [1]. Azimuthal momentum space distributions and the production of high transverse momentum (p_T) hadrons, presumably from parton scatterings involving large momentum transfer, are both thought to probe the early stages of these collisions [2, 3].

The ratio of particle yields in Au+Au and p+p collisions scaled by the number of binary nucleon-nucleon collisions (R_{AA}) has been measured for charged hadrons and neutral pions [4]. These measurements show a suppression, with respect to the number of binary nucleon-nucleon collisions, of moderate to high p_T particle yields in central Au+Au collisions, with the neutral pion yield suppressed more than the charged hadron yield for $p_T \lesssim 5$ GeV/c. The quenching of jets traversing the high density matter created in the collision [2] and gluon density saturation [5] have been proposed to explain this suppression.

The azimuthal distribution of particle momenta can be expressed in terms of the expansion; $dN/d\phi \propto 1 + \sum_n 2v_n \cos n\,(\phi - \Psi_r)$, where ϕ is the azimuth angle of the particle momentum and Ψ_r is the reaction plane angle (*ie.* the azimuth angle of the vector connecting the centers of the nuclei). The second coefficient v_2, commonly called *elliptic flow*, has been measured for identified particles [6, 7] and charged hadrons [8, 9]. At low p_T ($p_T < 1$ GeV/c) v_2 indicates that the conversion of spatial anisotropy to momentum anisotropy reaches the hydrodynamical limit (where local thermal equilibrium has been assumed) [3, 10, 11]. At intermediate p_T ($1.5 < p_T < 4$ GeV/c), however, the charged hadron v_2 saturates at a value approximately independent of p_T [8, 9] and below hydrodynamical model predictions. Models using large parton energy loss [12] and parton transport in an opaque medium [13] have been discussed in relation to the magnitude and centrality dependence of the charged hadron v_2 at large p_T.

If a partonic state exists prior to hadronization, the process of particle formation at intermediate p_T, by string fragmentation, parton fragmentation [14] or quark coalescence [15, 16, 17, 18], may lead to a dependence of v_2 and R_{AA} on particle type. As such, these measurements may provide information on the existence and nature of an early partonic state.

Like R_{AA}, the ratio of the yields in central and peripheral collisions (R_{CP}) is also a measure of the nuclear modification of particle production:

$$R_{CP}(p_T) = \frac{[dn/(N_{binary}dp_T)]^{central}}{[dn/(N_{binary}dp_T)]^{peripheral}},$$

where n is the particle yield per event and N_{binary} [19] is the number of binary nucleon-nucleon collisions. In this Letter, we report the measurement of v_2 and R_{CP} at mid-rapidity, $|y| \leq 1.0$, for K_S^0 and lambda (Λ) + antilambda ($\overline{\Lambda}$) with $0.2 < p_T < 6.5$ GeV/c and $0.4 < p_T < 6.0$ GeV/c respectively, along with R_{CP} for charged kaons ($K^\pm$) from $0.2 < p_T < 3.0$ GeV/c, in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

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 [20]. The K_S^0 and $\Lambda(\overline{\Lambda})$ were reconstructed from the topology of the decay channels, $K_S^0 \rightarrow \pi^+ + \pi^-$ 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. [7, 21]. The $K^\pm$ are identified from one-prong decays as described in Ref. [22]. 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 tracks. To avoid autocorrelations, tracks associated with a K_S^0, Λ or $\overline{\Lambda}$ decay vertex are excluded from the calculation of Ψ_r.

Sources of systematic error in the calculation of v_2 are correlations unrelated to the reaction plane (non-flow effects), estimation of the yield from the invariant mass distributions, the p_T resolution ($\delta p_T/p_T$), and biases introduced by the cuts used in the analysis. Table I lists the dominant systematic errors. The systematic error in v_2 associated with the yield extraction is found to be small and the non-flow systematic error is dominant. The effect of non-flow on charged particle v_2 has been estimated

TABLE I: The systematic errors from background (bg), non-flow effects (n-f), and the efficiency calculation (eff) are listed for v_2 (0–80%) and R_{CP} (0–5%/40–60%) at three p_T values along with the p_T resolution ($\delta p_T/p_T$). The values listed are absolute errors for v_2 and relative errors for R_{CP}.

	K_S^0 ($K^\pm$)			$\Lambda + \overline{\Lambda}$		
p_T (GeV/c)	1.0	2.5	4.0	1.0	2.5	4.0
v_2 (bg)	+0.000 +0.001	+0.001 −0.007	+0.003 −0.018	+0.001 −0.007	+0.005 −0.001	+0.005 −0.001
v_2 (n-f)	+0.00 −0.01	+0.00 −0.04	+0.00 −0.03	+0.00 −0.01	+0.00 −0.04	+0.00 −0.04
R_{CP} (bg)	±0.04 (±0.02)	±0.02 (±0.06)	±0.08	±0.02	±0.04	±0.06
R_{CP} (eff)	±0.10 (±0.05)	±0.10 (±0.09)	±0.10	±0.10	±0.10	±0.10
$\delta p_T/p_T$	±0.012 (±0.015)	±0.027 (±0.057)	±0.030	±0.016	±0.027	±0.037

using a four-particle cumulant analysis [8]. Nuclear modification of jet production and fragmentation could lead to a particle-type dependence in these non-flow effects. The four-particle cumulant method can be adapted to study the non-flow contributions to $\Lambda + \overline{\Lambda}$ and K_S^0 v_2 but requires a larger data sample than is currently available. The effect of standard jet fragmentation on v_2 was examined using superimposed p+p collisions generated with PYTHIA [23]. Within the measured p_T region, no significant difference was seen between $\Lambda+\overline{\Lambda}$ and K_S^0 from this non-flow effect. In this analysis, we assume a similar magnitude of non-flow contribution to $\Lambda + \overline{\Lambda}$ and K_S^0 v_2. Contributions to the systematic errors for R_{CP} (Table I) come from the determination of the detector efficiency, extraction of the yields, $\delta p_T/p_T$, and uncertainty in the model calculation of N_{binary}.

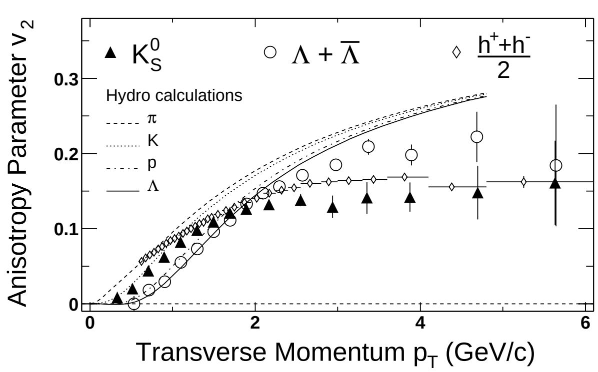

FIG. 1: The minimum-bias (0–80% of the collision cross section) $v_2(p_T)$ for K_S^0, $\Lambda + \overline{\Lambda}$ and $h^\pm$. The error bars shown are statistical only. Hydrodynamical calculations of v_2 for pions, kaons, protons and lambdas are also plotted [10].

Fig. 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. [9]. Fig. 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 [7]. This Letter establishes the particle-type dependence of the v_2 saturation at intermediate p_T. Contrary to hydrodynamical calculations, where at a given p_T, heavier particles have smaller v_2 values, at intermediate p_T, $v_{2,\Lambda+\overline{\Lambda}} > v_{2,K}$. The p_T scale where v_2 deviates from the hydrodynamical prediction is ~ 2.5 GeV/c for $\Lambda+\overline{\Lambda}$ and ~ 1 GeV/c for K^0_S.

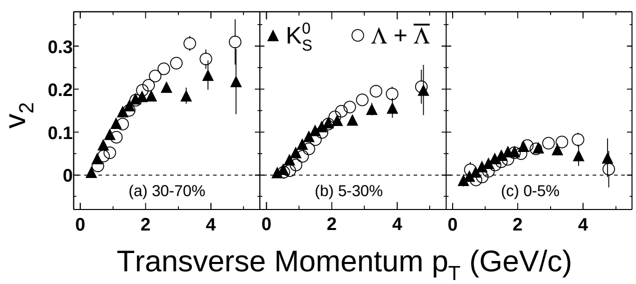

FIG. 2: The v_2 of K^0_S and $\Lambda+\overline{\Lambda}$ as a function of p_T for 30–70% (most central), 5–30% and 0–5% of the collision cross section. The error bars represent statistical errors only. The non-flow systematic errors for the 30–70%, 5–30% and 0–5% centralities are -25%, -20% and -80%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

Fig. 2 shows v_2 of K^0_S and $\Lambda+\overline{\Lambda}$ as a function of p_T for three centrality intervals, 30–70%, 5–30%, and 0–5% of the geometrical cross section. The p_T dependence of the v_2 from all three centrality bins has a similar trend, with a saturation at intermediate p_T. The values of v_2 at saturation show a particle-type and centrality dependence.

The particle-type dependence of the nuclear modification factors R_{AA} or R_{CP} may also be a sensitive probe of the early collision dynamics and the hadronization process. Binary collision scaling, i.e. $R_{CP} = 1$, indicates that the yield is proportional to the number of binary nucleon-nucleon collisions. Fig. 3 shows R_{CP} for K^0_S, $K^{\pm}$, 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 binary collision scaling without medium modification. The bands in Fig. 3 represent the expected values of R_{CP} for binary and participant (N_{part}) scaling including systematic variations from the calculation [19].

The kaon and (anti-)lambda yields are suppressed by different magnitudes and the p_T scales associated with the onset of the high p_T suppression are different. For most of the intermediate p_T region, $\Lambda+\overline{\Lambda}$ R_{CP} coincides with binary collision scaling, while the kaon R_{CP} is significantly below unity. For both species, the p_T where R_{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_{CP} values for K^0_S and $\Lambda+\overline{\Lambda}$ are approaching the value of the charged hadron R_{CP}. The particle type and p_T dependence of v_2 and R_{CP} may reveal a transition from bulk partonic matter hadronization to single parton fragmentation. Our measurements indicate that the transition sets in around $p_T \sim 4$–5 GeV/c. At high p_T, the particle-type dependence of R_{CP}, disappears within errors, perhaps indicating that single parton fragmentation dominates the features of R_{CP}. Nuclear modifications such as shadowing and the Cronin effect [24] may also affect R_{CP} [25, 26].

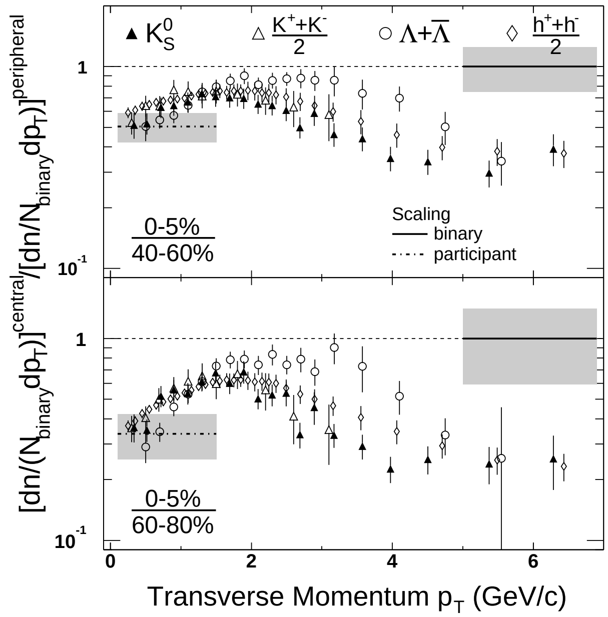

FIG. 3: R_{CP} for K^0_S, $K^{\pm}$, and $\Lambda+\overline{\Lambda}$ at mid-rapidity calculated using centrality intervals, 0–5% vs. 40–60% (top) and 0–5% vs. 60–80% of the collision cross section (bottom). The error bars shown on the points include both statistical and systematic errors. The widths of the gray bands represent the uncertainties in the model calculations of N_{binary} and N_{part}. We also show the charged hadron R_{CP} measured by STAR for $\sqrt{s_{NN}} = 200$ GeV [19].

A *surface emission* scenario, where partons traversing a dense medium experience large energy losses, has been discussed in relation to the large, p_T-independent v_2 measured for charged hadrons [12]. In this mechanism, a larger energy loss would lead to a higher v_2 and a larger suppression of particle production. This scenario, however, is inconsistent with our measurements of v_2 and R_{CP} of kaons and $\Lambda+\overline{\Lambda}$ at intermediate p_T. The smaller suppression of the $\Lambda+\overline{\Lambda}$ yield contradicts the larger azimuthal anisotropy seen in the $\Lambda+\overline{\Lambda}$ v_2. These calculations do not, however, account for how the process of hadronization may change the observed v_2.

Nuclear enhancement of hadron yields at intermediate

p_T has been observed in p+A collisions at lower beam energy (Cronin effect [24]), with a larger enhancement for baryons than mesons [25]. The magnitude of the Cronin effect is expected to decrease with increasing beam energy [26]. The magnitude has not, however, been established experimentally at RHIC energy for kaons, lambdas, or antilambdas. Theoretical calculations, such as those involving initial parton scatterings off cold nuclear matter (e.g. [27]), don't reproduce the particle-type dependence of the enhancement factor observed in p+A collisions. Alternatively, the strong particle-type dependence here may indicate a nuclear modification of the parton fragmentation into baryons and mesons or the presence of a multi-parton particle formation mechanism such as coalescence [18] or recombination [17] in p+A collisions. These mechanisms are beyond the framework of many existing theoretical models for the Cronin effect.

The absence of a significant suppression with respect to binary scaling of the $\Lambda+\overline{\Lambda}$ yield at intermediate p_T in central Au+Au collisions may also indicate the presence of dynamics beyond parton energy loss and standard fragmentation. The larger $\Lambda+\overline{\Lambda}$ R_{CP} at intermediate p_T means that the (anti)lambda yield increases with the parton density of the collision fireball much faster than the meson yield. Stronger dependence on parton density for baryon production is naturally expected from multi-parton mechanisms such as gluon junctions [28], quark coalescence [15], or recombination [17]. Fig. 4 shows v_2 of K^0_S 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^0_S and $\Lambda+\overline{\Lambda}$, within errors, v_2/n vs p_T/n is the same for both species above $p_T/\mathrm{n} \sim 0.8$ GeV/c. This behavior is consistent with a scenario where hadrons at intermediate p_T are formed from bulk partonic matter by coalescence of co-moving quarks so that v_2/n vs p_T/n reveals the momentum space azimuthal anisotropy that partons develop from the collision ellipsoid, e.g. Ref. [15]. The ordering of the K^0_S, $h^{\pm}$, and $\Lambda+\overline{\Lambda}$ v_2 is inconsistent, however, with the coalescence scenario in Ref. [16], where $v_{2,\pi} = v_{2,p} > v_{2,\Lambda} > v_{2,K}$.

In summary, we have reported the measurement of v_2 and R_{CP} up to p_T of 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^0_S and $\Lambda+\overline{\Lambda}$. At intermediate p_T, however, hydrodynamics no longer describes the particle production. For K^0_S, v_2 saturates earlier and at a lower value than for $\Lambda+\overline{\Lambda}$. In addition, R_{CP} shows that the kaon yield in central collisions is suppressed more than the (anti-)lambda yield. At intermediate p_T, the $\Lambda+\overline{\Lambda}$ yield in central Au+Au collisions is close to expectations from binary scaling of peripheral Au+Au collisions. At high p_T, the R_{CP} of K^0_S, $\Lambda+\overline{\Lambda}$ and charged hadrons are approaching the same value. The measured features in the kaon and (anti-)lambda v_2 and R_{CP} may indicate the presence of dynamics beyond the framework of parton energy loss followed by fragmentation. The particle- and p_T-dependence of v_2 and R_{CP}, particularly at intermediate p_T, may provide a unique means to investigate the anisotropy and hadronization of the bulk dense matter formed in nucleus-nucleus collisions at RHIC.

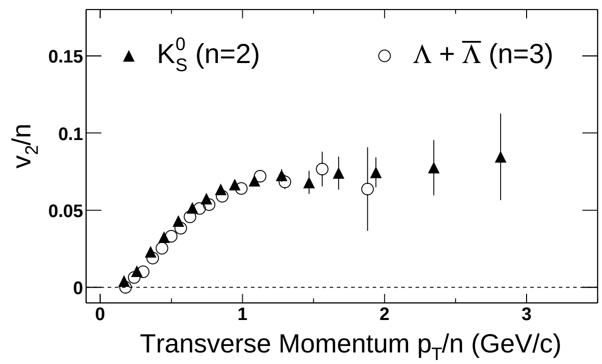

FIG. 4: The v_2 parameter for K^0_S and $\Lambda+\overline{\Lambda}$ scaled by the number of constituent quarks (n) and plotted versus p_T/n.

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