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

J. Adams,3 C. Adler,12 M.M. Aggarwal,25 Z. Ahammad,38 J. Amonett,17 B.D. Anderson,17 M. Anderson,5 D. Arkiphaskin,11 G.S. Averichev,10 S.K. Baidyal,16 J. Balewski,13 O. Barannikova,28,10 L.S. Barnby,3 J. Baudot,15 S. Bekele,24 V.V. Belaga,10 R. Bellwied,43 J. Berger,12 B.I. Bezverkhny,43 S. Bhardwaj,29 P. Bhaskar,38 A.K. Bhati,25 H. Bichsel,40 A. Billmeier,31 L.C. Bland,2 C.O. Blyth,3 E.E. Bonner,39 M. Botje,23 A. Boucham,34 A. Brandin,21 A. Bravar,2 R.V. Cadman,1 X.Z. Cai,33 H. Caines,43 M. Calderón de la Barca Sánchez,2 J. Carroll,18 J. Castillo,18 M. Castro,41 D. Cebra,5 P. Chaloupka,9 S. Chattopadhyay,38 H.F. Chen,32 Y. Chen,6 S.P. Chernenko,10 M. Cherney,8 A. Chikanian,34 B. Choi,36 W. Christie,2 J.P. Coffin,15 T.M. Cornier,41 J.G. Cramer,40 H.J. Crawford,4 D. Das,38 S. Das,38 A.A. Derevschikov,27 L. Didenko,2 T. Dietel,12 W.J. Dong,6 X. Dong,32,18 J.E. Draper,5 F. Du,43 A.K. Dubey,14 V.B. Dumin,10 J.C. Dunlop,3 M.R. Dutta Majumdar,38 V. Eckardt,19 L.G. Efimov,10 V. Emelianov,21 J. Engel,4 G. Eppley,30 B. Erazmus,34 M. Estienne,34 P. Fanchi,2 V. Faine,2 J. Faivre,15 R. Fatemi,13 K. Filimonov,18 P. Filip,9 E. Finch,43 Y. Fisyak,2 D. Flierl,12 K.J. Foley,2 J. Fu,42 C.A. Gagliardi,35 N. Gagnonvchi,10 J. Gans,34 M.S. Ganti,38 L. Gaudichet,34 M. Germain,15 F. Geurts,30 V. Ghazikhanian,6 P. Ghosh,38 J.E. Gonzalez,6 O. Grachov,41 V. Grigoriev,21 S. Gronstal,8 D. Grosnick,37 M. Guedon,15 S.M. Guertin,4 A. Gupta,46 E. Gushin,21 T.D. Gutierrez,5 T.J. Hallman,2 D. Hardtke,18 J.W. Harris,43 M. Heinz,43 T.W. Henry,35 S. Heppelmann,26 T. Herston,28 B. Hippolyte,43 A. Hirsch,28 E. Hjort,18 G.W. Hoffmann,36 M. Horsley,34 H.Z. Huang,6 S.L. Huang,32 T.J. Humanic,24 G. Igo,6 A. Ishihara,36 P. Jacobs,18 W.W. Jacobs,13 M. Janik,39 H. Jiang,6,18 I. Johnson,18 P.G. Jones,3 E.G. Judd,4 S. Kabana,43 M. Kaneta,18 M. Kaplan,7 D. Keane,17 V. Yu. Khodyrev,27 J. Kiryluk6 A. Kisiel,39 J. Klay,18 S.R. Klein,18 A. Klyachko,13 D.D. Koetke,37 T. Kollegger,12 M. Kopytine,17 L. Kotchenda,21 A.D. Kovaltenko,10 M. Kramer,22 P. Kravtsov,21 I.V. Kravtsov,21 K. Krueger,1 C. Kuhn,15 A.I. Kulikov,10 A. Kumar,25 G.J. Kunde,43 C.L. Kunz,7 R.Kh. Kutuev,11 A.A. Kuznetsov,10 M.A.C. Lamont,3 J.M. Landgraf,2 S. Lange,12 C.P. Lansdell,26 B. Lasiik,24 F. Laue,2 J. Laurent,2 A. Lebedev,2 R. Lednický,10 M.J. LeVine,2 C. Li,32 Q. Li,41 S.J. Lindenbaum,22 M.A. Lisa,24 F. Liu,24 L. Liu,24 Z. Liu,24 Q.J. Liu,40 T. Ljubicic,2 W.J. Llope,30 H. Long,9 R.S. Longacre,2 M. Lopez-Noriega,24 W.A. Love,7 T. Ludlam,2 D. Lynn,2 J. Ma,6 Y.G. Ma,33 D. Magestro,24 S. Mahajan,16 L.K. Mangatopa,14 R. Majka,43 R. Manweiler,37 S. Margetis,17 C. Markert,43 L. Martin,34 J. Marx,18 H.S. Matia,18 Yu.A. Matulenko,72 T.S. McShane,8 F. Meissner,18 Y. Melnick,27 A. Mescholin,27 M. Messer,2 M.L. Miller,43 Z. Milesovič,7 N.G. Minaev,27 C. Mironov,17 D. Mishra,14 J. Mitchell,30 B. Mohanty,38 L. Mohlar,28 C.F. Moore,36 M.J. Mora-Corral,19 D.A. Morozov,27 V. Morozov,18 M.M. de Moura,31 M.G. Munhoz,31 B.K. Nandi,38 S.K. Nayak,16 T.K. Nayak,38 J.M. Nelson,3 P. Nevskii,2 V.A. Nikitin,11 L.V. Nogach,27 B. Norman,17 S.B. Nurusheva,27 G. Ovchinnikov,18 A. Ogawa,2 V. Okorokov,21 M. Oldenburg,18 D. Olson,18 G. Paic,24 S.U. Pandey,41 S.K. Pal,38 Y. Panebratsev,10 S.Y. Panitkin,2 A.I. Pavlinov,41 T. Pawlak,39 V. Perevozchikov,24 C. Perkins,2 W. Peryt,39 V.A. Petrov,11 S.C. Phatak,14 R. Picha,5 M. Planinčar,14 J. Pluta,39 N. Porile,28 J. Porter,2 A.M. Poskanzer,18 M. Potekhin,2 E. Potrebenikov,10 B.V.K.S. Potukuchi,16 D. Prindl,40 C. Pruneau,41 J. Putschke,19 G. Rai,18 G. Rakness,13 R. Ranjivala,29 S. Ranjivala,29 O. Ravel,34 R.L. Ray,36 S.V. Razin,10 D. Reichhold,28 J.G. Reid,40 G. Renaud,34 F. Retiere,18 A. Ridger,21 H.G. Ritter,18 J.B. Roberts,30 O.V. Rogachevskiy,10 J.L. Romero,5 A. Rose,41 C. Roy,34 L.J. Ruan,32 R. Sahoo,14 I. Sakrejda,18 S. Salur,43 J. Sandweiss,43 I. Savin,11 J. Schambach,36 R.P. Scharenberg,28 N. Schmitz,19 L.S. Schroeder,18 K. Schweda,18 J. Seger,8 D. Seliverstov,21 P. Seyboth,19 E. Shalaliev,10 M. Shao,32 M. Sharma,25 K.E. Shestakov,27 S.S. Shmamishkin,10 R.N. Singaraju,38 F. Simon,19 G. Skoro,10 N. Smirnov,43 R. Snellings,23 G. Sood,25 P. Sorensen,18 J. Sowinskas,13 H.M. Spinka,1 B. Srivastava,28 S. Stanislaus,37 R. Stock,32 A. Stolpovsky,41 M. Strikhanov,21 B. Stringfellow,28 C. Struck,12 A.A.P. Suade,13 E. Sugarbaker,24 C. Suire,2 M. Sumbera,9 B. Surrow,2 T.J.M. Symons,18 A. Szanto de Toledo,31 P. Szarvas,39 A. Tai,9 J. Takahashi,31 A.H. Tang,2,23 D. Thein,6 J.H. Thomas,18 V. Tikhonov,21 M. Tokarev,10 M.B. Tonjes,20 T.A. Trainor,40 S. Trendenthal,6 R.E. Tribble,35 M.D. Trivedi,38 V. Trofimov,21 O. Tsai,6 T. Ullrich,2 D.G. Underwood,1 G. Van Buren,2 A.M. VanderMolen,20 A.N. Vasilev,27 M. Vasilev,35 S.E. Vigdor,13 Y.P. Vinyo,38 S.A. Voloshin,41 W. Waggoner,8 F. Wang,28 G. Wang,17 X.L. Wang,32 Z.M. Wang,32 H. Ward,36 J.W. Watson,17 R. Wells,24 G.D. Westfall,20 C. Whitten Jr.,6 H. Wieman,24 R. Willson,24 S.W. Wissink,13 R. Witt,43 J. Wood,6 J. 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We present STAR measurements of the azimuthal anisotropy parameter $v_2$ and the binary-collision scaled centrality ratio $R_{CP}$ for kaons and lambdas ($\Lambda + \bar{\Lambda}$) at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. In combination, the $v_2$ and $R_{CP}$ particle-type dependencies contradict expectations from partonic energy loss followed by standard fragmentation in vacuum. We establish $p_T \approx 5 \text{ GeV}/c$ as the value where the centrality dependent baryon enhancement ends. The $K_0^0$ and $\Lambda + \bar{\Lambda}$ $v_2$ 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 ultra-relativistic heavy-ion collisions [1, 2, 3, 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 ($\phi$) of the momentum-space distribution; $dN/d\phi \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_{RP})$. 

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where $\Psi_{RP}$ 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 \[1, 3\]. At low $p_T$ ($p_T < 1$ GeV/c), the dependence of $v_2$ on particle mass $\[2, 4\]$ is consistent with hydrodynamic calculations where local thermal equilibrium of partons has been assumed $\[2, 3, 4\]$.

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 $N_{\text{bin}}$. The $N_{\text{bin}}$ scaled centrality ratio $R_{CP}$ is a measure of the particle production’s dependence on the collision system’s size and density:

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

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 $N_{\text{bin}}$ scaling (i.e. $R_{CP}$ and the closely related nuclear modification factor $R_{AA}$ are below unity) $\[12, 13\]$. 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 $\[1, 2, 3, 5\]$ models for hadron formation are an alternative to the fragmentation models commonly used in energy loss calculations $\[12\]$. 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 mid-rapidity ($|y| < 1$) for $K_S^0$ and $A + \bar{A}$ for $0.2 < p_T < 6.5$ and $0.4 < p_T < 6.0$ GeV/c respectively along with $R_{CP}$ for $K^+$ from $0.2 < p_T < 3.0$ GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The $K_S^0$ and $A + \bar{A}$ 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 $1.6 \times 10^6$ minimum–bias trigger events and $1.5 \times 10^6$ central trigger events from the Solenoidal Tracker at RHIC (STAR) experiment $\[10\]$. The $K_S^0$ and $A(\Lambda)$ were reconstructed from the topology of the decay channels, $K_S^0 \rightarrow \pi^+ + \pi^-$ and $A(\Lambda) \rightarrow p + \pi^- (\bar{p} + \pi^+)$. A detailed description of the analysis, such as track quality, decay vertex topology cuts, and detection efficiency, can be found in Refs. $\[3, 17, 18\]$. The $K^+$ are identified from one-prong decays as described in Ref. $\[19\]$. For both $v_2$ and $R_{CP}$, no difference is seen between $A$ and $\bar{A}$ 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 $\eta$ is the pseudorapidity. To avoid auto-correlations, tracks associated with a $K_S^0$, $A$ or $\bar{A}$ decay vertex are excluded from the calculation of $\Psi_{RP}$.

### Table I: The relative systematic errors (%) from background (bg) and non-flow effects (n-f) 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.

| $p_T$ (GeV/c) | $K_S^0$ | $K^+$ | $A + \bar{A}$ |
|---------------|---------|-------|----------------|
| 1.0           | 1.0     | 1.0   | 1.0            |
| 2.5           | 2.5     | 2.5   | 2.5            |
| 4.0           | 4.0     | 4.0   | 4.0            |

Systematic errors in the calculation of $v_2$ are due to correlations unrelated to the reaction plane (non-flow effects) and uncertainty in estimates of the background in the invariant mass distributions. Table II lists the dominant systematic errors. The systematic error in $v_2$ associated with the yield extraction (background) is found to be small and the non-flow systematic error is dominant. We estimate the non-flow contribution by comparing charged particle $v_2$ from a reaction-plane analysis and a four-particle cumulant analysis $\[4\]$. The four-particle cumulant analysis is thought to be insensitive to non-flow effects but leads to larger statistical errors. Any difference between the methods is assumed to arise from non-flow contributions. The non-flow contribution to $v_2$ has not been established experimentally for identified particles. We examined the effect of standard jet fragmentation on $K_S^0$ and $A + \bar{A}$ $v_2$ using superimposed p+p collisions generated with PYTHIA $\[21\]$. Within the measured $p_T$ region, no significant differences are seen between $A + \bar{A}$ and $K_S^0$ non-flow effects from this source. We assume a similar magnitude of non-flow contribution to $A + \bar{A}$ and $K_S^0$ $v_2$ 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 non-flow contributions to both $A + \bar{A}$ and $K_S^0$ $v_2$. Contributions to the systematic errors for $R_{CP}$ come from the determination of the detector efficiency, extraction of the yields and uncertainty in the model calculation.
of $N_{\text{bin}}$.

Fig. 1 shows minimum-bias $v_2$ for $K_S^0$, $\Lambda + \bar{\Lambda}$ 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 [5]. 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 $\Lambda + \bar{\Lambda}$ and $\sim 1$ GeV/$c$ for $K_S^0$.

Fig. 2 shows $v_2$ of $K_S^0$ and $\Lambda + \bar{\Lambda}$ 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 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 $K_S^0$ and $\Lambda + \bar{\Lambda}$ 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.

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, $\Lambda + \bar{\Lambda}$ yields should be more suppressed than kaon yields. Fig. 3 shows $R_{\text{CP}}$ for $K_S^0$, $K^\pm$, and $\Lambda + \bar{\Lambda}$ using the 5% most central collisions, normalized by peripheral collisions (40-60% and 60-80%). For charged hadrons, these peripheral bins approximately follow $N_{\text{bin}}$ scaling without medium modification [13]. The bands in Fig. 3 show the expected values of $R_{\text{CP}}$ for binary and participant ($N_{\text{part}}$) scaling including systematic variations from the calculation [13]. For most of the intermediate $p_T$ region, $R_{\text{CP}}$ for $\Lambda + \bar{\Lambda}$ is similar to expectations of $N_{\text{bin}}$ scaling and $R_{\text{CP}}^{K_S^0} < R_{\text{CP}}^{\Lambda}$. The $p_T$ scales associated with the saturation and reduction of $R_{\text{CP}}$ also depend on the particle type. For both species, the $p_T$ where $R_{\text{CP}}$ 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/$c$), $R_{\text{CP}}$ values for $K_S^0$ and $\Lambda + \bar{\Lambda}$ are consistent with the value for charged hadron $R_{\text{CP}}$, 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 $R_{\text{CP}}$ 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 may affect $R_{\text{CP}}$ but they are not expected to give rise to such a large variation with particle-type (e.g. [21]). At lower beam energy, the enhancement of yields in p+A collisions at intermediate $p_T$ (i.e. the Cronin effect) 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 non-flow deserve further investigation, the particle-type and $p_T$ dependence of $v_2$ and $R_{\text{CP}}$ may reveal a cross-over from a $p_T$ region dominated by bulk partonic matter hadronization to one dominated by single parton fragmentation. Our measurements indicate that the cross-over would occur at $p_T \approx 4$–5 GeV/$c$.

The larger $\Lambda + \bar{\Lambda}$ $R_{\text{CP}}$ at intermediate $p_T$ shows that the $\Lambda + \bar{\Lambda}$ yield increases with parton density faster than the kaon yield. Multi-parton mechanisms such as gluon junctions [24], quark coalescence, or recombination 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. Fig. 2 shows $v_2$ of $K_S^0$ and $\Lambda + \bar{\Lambda}$ as a function of $p_T$, where...
At mid-rapidity calculated using centrality intervals, \( \Lambda \) are \( \frac{2}{s_{\Lambda}} \) at intermediate \( R_{CP} \), within errors, and \( \Lambda + \bar{\Lambda} \) 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. The measured features at intermediate \( p_T \) are consistent with the presence of multi-parton particle formation mechanisms beyond the framework of parton energy loss followed by standard fragmentation. The particle- 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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